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Analysis of the response of wheat to N and P fertilization under nonuniform environmental conditions in southeast Buenos Aires Province, Argentina

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Analysis of the response of wheat to N and P fertilization under nonuniform environmental conditions in southeast Buenos Aires Province, Argentina

by

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CHAPTER I. INTRODUCTION

Characterization of the Problem

The yield level of any crop and the presence or absence of yield response to mineral fertilization depend upon many uncontrolled soil and climatic factors which make up the crop environment.

Thus, the amount of fertilizer required for the most economic production of crops in a certain region commonly varies in a large fashion throughout the region and from year to year. As a consequence potential profits are lost each year, either because insufficient fertilizer is applied to reach the point of maximum profit or too much is applied and a waste of capital and possible yield depression occur, reducing the farmer's profit even more.

In agricultural regions like the one under study in which the cost of fertilizer is comparatively high relative to the price received for the selling of the wheat grain, the need for accurate estimations of fertilizer requirements is a matter of vital importance.

There are, however, severe practical difficulties to be overcome. Funds for research are usually limited, large areas have to be covered with few trained research personnel and a lack of adequate climatological information is generally a common feature.

The most usual sequence of research to determine the needs for fertilizers in a given region traditionally has been done in two steps. First, preliminary field experiments with different fertilizers are carried out at several sites throughout the region for one or more crops. The second and more important step is to assess the specific fertilizer requirements for a given crop to be grown in an individual farmer's field throughout the region. For this second part of the investigation, the selection of experimental sites over several years, the selection of an appropriate treatment and experimental design, the collection of both plot and site data, and the complete analysis of the gathered information are considered the fundamental steps.

The use of farmer's fields in planning a series of experiments in soil fertility studies is a well-recognized practice, but if the selection of a site is not carefully planned, disappointing results may be obtained. If the population to be studied is to be confined to a geographically defined region, the selection procedure might include certain restrictions to insure a uniform distribution of experimental sites throughout the region. Certain areas within the defined population might be more important than others and the sampling could be done in proportion to the weights of importance assigned to the various areas. The major hypothesis of research projects of this type is that information from one set of experiments may be transferred to sites within the same soil family. The vehicle for transfer is a model estimated from the experimental data (Cady, 1974).

A great deal of preliminary work has to be accomplished before the final selection of the experimental sites can be achieved satisfactorily. For instance, a good semi-detailed soil survey and classification study is considered almost essential for this purpose. Reliable laboratory techniques are needed to accurately quantify the different site variables. The calibration of soil tests in terms of fertilizer requirement will provide the ultimate working basis for soil testing laboratories.

Finally, the experience of the researchers in the interpretation and understanding of the relationships among the variables and the reasons for their inclusion in the initial analysis is considered to be the most important ingredient in the success of the project.

The Problem Area

The area under study is located in the southeastern part of the Buenos Aires province in Argentina, encompassed between the parallels 37°40' and 39° south and the meridians 57°30' to 62 degrees west. It is a region of diversified agriculture in which cattle still play a strong role. The main crops by acreage are wheat, oats, barley, sunflowers, flax and potatoes.[1] Grain sorghum is considered the main summer-forage crop, but both permanent and temporary pastures are by far the predominant grazing sources. Grain producers in this area have adopted many of the production practices common in the United States and other major grain producing countries. However, the use of fertilizers is comparatively very low and has increased rather slowly. In Argentina national fertilizer use has averaged about 2.5 kg per ha[2] in each of the last ten years, compared with the rest of South America which has averaged around 18.5 kg per ha.[2] Nevertheless the amount of N and P used has increased consistently over the last twelve years (FAO, 1976).

There appear to be several reasons for the low consumption of fertilizers. First, the cost of fertilizer to the average Argentine farmer has been generally so large relative to the usual market price of grain, that adverse weather may have resulted in financial losses even though a fairly respectable increase in yield per ha was obtained in comparison to the yield that would have resulted without fertilization. Second, over 90 percent of all phosphorus fertilizers must be imported currently, thus contributing to the high cost. For example, the cost of nitrogen, which is

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[1]Corn is produced as a summer row crop in certain parts of the area, and could be considered as an alternative to potatoes.

[2]Per ha of arable land and land under permanent crops.

produced locally in the ammonia form, has been more than 2 1/2 times higher to an Argentine farmer than to a United States farmer, and the cost of urea, which is also locally produced, has been about 1 1/2 times higher. Also, until recently import duties were collected on phosphorous fertilizers.

Third, most of the current wheat varieties being used by the farmers were developed mainly to withstand several fungal diseases or to increase grain quality, but it was not until 1968 that research produced the first variety adapted to high soil fertility levels. Actually four or five varieties selected to withstand high rates of fertilization are being adopted by the farmers.

Fourth, with favorable weather, most of the soils (except where they have been cropped for many years without interruption) will still produce crops profitably at actual levels of returns and costs without fertilization. It is the belief of this author that farmers in Argentina have not yet faced the pressures of increased land cost, acreage allotments, or high land taxes that have forced farmers in the United States and other major agricultural regions of Europe to continually strive for higher levels of output per unit of land.

But, with an increasing world population, creating a continuous increasing demand for food supply, it is expected that this situation will change in the near future. So, strategic research projects have to be developed to reduce the time period between initiation of research and recommendations. This implies going directly to a relatively large number of experiments (as compared with the past) in a single stage of experimentation. The needed work is both expensive and time consuming; therefore, it is very important to assess carefully the results of such projects during their course of action and to modify whatever is necessary on the basis of local experience.

In an attempt to investigate in more detail the relationships between soil fertility, management, climate and crop production factors within some agricultural areas of the country, the Argentine government has conducted several cooperative projects with FAO, CIMMYT, INRA and other well-known agricultural research institutions during the last fifteen years. In the area under study a cooperative program between FAO and INTA (the National Institute for Agricultural Technology) was implemented and carried out between 1971 and 1975. The objectives of this program were to assess the importance of the use of fertilizer and other well-known soil and crop management techniques for the productivity of the principal crops throughout the region. Many improvements have been accomplished, and large amounts of data have been recorded. Hence, knowledge of the factor-yield relationship for some crops has been increased.

However, due to the expansiveness (twelve million hectares) and diversity of the area, further analyses of the data are needed to predict yield and input requirements at the individual farm level.

The main objective of this dissertation is to analyze and interpret the information generated by this program on wheat productivity from 1972 to 1975.

This objective will be accomplished by:

a. an analysis of the current methodology used to assess the response of crops to fertilization;

b. the development of a yield function to quantify the influence of some environmental and management factors on wheat production, using the information collected from seventy-two experimental trials located throughout the wheat area in the southeastern part of the Buenos Aires Province; and

c. the identification of areas where additional research should be conducted to help in the assessment of future research priorities.

CHAPTER II. LITERATURE REVIEW

Factors Which Affect the Crop Response to Fertilizers

Crop yields are influenced by many factors. Fitts (1959), expressed yield as a function of crop, soil, climate and management. Each of these general factors have several components, e.g., crop involves kind, variety and population. Soil is generally regarded as a more complex factor combining a multitude of physical, chemical and biological properties which in turn determine support and nutrition for the crop. Among the physical properties, the texture and structure of the soil horizons will determine the retention and flow of soil moisture, aeration, root development and nutrient uptake. Within the chemical properties the available levels of the essential mineral nutrients, the soil reaction (degree of acidity or alkalinity), the amount or concentrations of neutral salts, and the ion exchange capacity of the colloidal system are the most likely to influence plant growth.

Climate includes aspects such as solar radiation, intensity and distribution components of precipitation, temperature, winds, and relative humidity. These last three together will account for the degree of atmospheric water demand. It also could include some detrimental factors such as hail or frost.

Management factors include tillage practices (type, number and timing), pest and weed control, fertilization, irrigation, selection of adequate varieties, planting rates, harvesting practices, etc.

There is very little doubt that soil deficiencies of the plant nutrients are related to the amounts of these nutrients present in the soil in available form. But there is ample evidence, however, that the amount of a given element in the soil is only one of the many factors that will determine whether the element needs to be applied to the soil and, if so, in what quantity. Since the climatic factors described earlier will influence greatly the nutrient uptake process for a particular combination of management and soil variables, the high dependency of the response on the climatic factors such as rainfall and solar radiation can be visualized easily. Then it is proper to say that the optimal fertilization levels of any plant nutrient may depend on a large array of soil, climatic and management factors.

The idea of considering a crop with all the factors that influence its yield in a given area as a production system for that particular crop is not new. It was perhaps Jenny in 1941 who made the first attempt to formalize the concept of a crop production system in terms of the productivity factors: climate, plant, man, soil and time.

Even though many researchers in crop production might have visualized, as Jenny did, the effect of these different factors upon yield and the necessity of their simultaneous measurement and evaluation, very few have attempted to do it in practice. Perhaps the lack of statistical knowledge and/or adequate computational facilities has been the main constraint.

Turrent in 1968 further developed and stressed the consideration of time as an important variable in any crop productivity study by the proposal of a static model. It is known that the rate of availability of many plant nutrients in the soil changes with time even within the limits of a given crop season. And soils vary in their quantitative and qualitative contents of other factors responsible for nutrient availability. By the same reasoning, as the root system of the crop is developing it is exploring new areas of the soil profile. As Turrent (1968) defined it, "The geometry of the individual productivity system (i.e., the plant and its environment) grows and assumes different forms as a function of time". And he further stated, "With a 3 coordinate Cartesian system of an arbitrary origin the volume that in a given moment is occupied by the individual productivity system can be described exactly, provided that the adequate mathematical function is known". Namely:

$G = f(x,y,z,t)$ where x,y and z are the axis of the 3 coordinates and t represents time.

Then, every one of the environmental factors can be looked upon as functions of the four coordinate system. However, none of the functions that relate the factors of productivity to the coordinate system x, y, z, t, seem to be exactly known. Furthermore, the functional model of the natural law of plant growth also remains unknown.

Because of the extreme complexity of the relationships between plant growth and production factors, most attempts to arrive at a general equation or set of equations, useful for predicting yield and input requirements for a given area, have been disappointing, even when great care was taken to measure the uncontrollable factors of production (Laird and Turrent, 1974).

Proper emphasis on the interactions among all production factors has not been achieved despite the large amounts of research time devoted to the collection and analysis of the data. Evaluation of these factors and their interactions has been hampered because of inadequate quantitative measurements for climate, past cropping practices, weeds, insects, varieties or other factors (Voss, Hanway, and Fuller, 1970).

Wright (1971) concurs in that the lack of proper information has been a major limitation in the developing of bio-economical models. He believes that the relatively small progress, achieved in this area in terms of the considerable research effort devoted to the analysis of agricultural systems, arises from the different research orientations of the analyst and synthesist. He further stated that "most of the analysis done so far has tended to be concentrated on small subsystems isolated from the rest of the integral system." While this has increased knowledge about the system at the micro-site level, there has not been a concomitant effort in synthesizing this knowledge into the context of the whole system.

Although the lack of data may prove to be a major limitation to the development of satisfactory agricultural models, it is the belief of the author that the mere attempt to develop such a model can play a useful role in terms of highlighting the type of information that is lacking. This information will often consist of approximations and simplifications of the biological relationships but in the absence of a demonstrated need there is no reason to expect that analytical scientists will produce such information.

One common feature in most crop production studies is the lack of integration between soil factors and plant physiology events. Several comprehensive studies involving soil, climate and management factors have been published in the last ten years, (Laird et al., 1969; Voss, 1969; Tejeda, 1973; Estrella, Turrent and Nuñez, 1975), just to mention a few. But, very seldom has the influence of the production factors at different physiological stages of the crop been assessed.

Yield Components of Wheat

Evans, Wardlaw and Fischer (1975) made an excellent review of the factors that determine the yield of the wheat crop. They stated that about half of the variation observed in wheat yields over a wide range of environments (climate, agronomic practices, and varieties) can be related to variation in leaf area duration.[1] Simpson (1968), Puckridge and Ratkowsky (1971) and Spiertz et al. (1971) have also found a close relationship between yield and leaf area duration in wheat. The fact that the leaf area of plants is greatly dependent on nutrition requires no documentation. But the way in which the different aspects of leaf growth are influenced by the supply of mineral nutrients is far from being fully understood. Furthermore, information on the effect of nutrition (under field condition) on the length of the functional life of leaves is scanty. In the wheat crops studied by Fischer and Kohn (1966) and Puckridge and Ratkowsky (1971) leaf area index reached its peak well before anthesis and fell progressively as water stress increased.

In modeling crop growth one crucial point is to deal with the effects of several stresses whose interactions are not known. It is also the rationale behind much contemporary

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[1] As defined by Watson et al. (1963), LAD is the integral of leaf area index with respect to time from earing to maturity.

discussion of whether the supply of assimilates (source) or the capacity for their storage (sink) limits crop yield.

There may be situations where neither source nor sink is the limiting factor, but rather the capacity to translocate assimilates from one to the other. Or other processes, such as water, nutrient uptake or transport, may be limiting (Evans, 1975). Where water or nitrogen supply is rapidly declining, as in the experiments described by Fisher and Kohn (1966), storage probably depends on the duration of photosynthetic activity, but with high nutrient and water levels the reverse may be the case. The photosynthetic activity of flag leaves late in grain filling could be very dependent on demand (King et al., 1967). Of the variation in yield not accounted for by differences in leaf area duration, most can be ascribed to differences in incoming radiation during grain filling (Evans, 1975). In the survey done by Welbank et al. (1968) where many experiments were analyzed they reported that the ratio of grain yield to leaf area duration increased linearly with increase in daily radiation during grain filling. Grain yield itself did not do so, however, tending to plateau at high radiation levels. The reason for this is presumably that the duration of grain filling is shorter at higher radiation levels cancelling any effect of greater photosynthesis (Evans, 1975).

Duration of grain growth has been quoted as a more powerful determinant of yield in wheat than is rate of grain growth because the latter is more likely to be limited by translocation or storage processes than by photosynthesis (Evans, 1975).

The storage capacity of a wheat crop depends on the number of ears per unit area, the number of spikelets per ear, the number of grains per spikelet, and individual grain size. The relative magnitude of these yield components varies substantially with the sequence of growing conditions, with features of agronomic management such as sowing density and fertilizer application, and of course with the cultivar used.

Both ear and spikelet number are determined well before anthesis, grain number around anthesis, and grain size between anthesis and maturity. Thus the storage capacity of a wheat crop can respond to environmental conditions almost untill maturity. Radiation and nutrient level during inflorescence growth, as well as temperature and day-length, influence spikelet number, while grain set is particularly influenced by light intensity and water supply just before and at anthesis. In the weeks following anthesis these factors also exert a marked effect on ultimate grain size, as does temperature throughout the grain filling period. This is in part due to the fact that grain filling is largely dependent on photosynthates formed after earing. Only 5-10% at the most of final grain weight is being derived from material stored in the stems before anthesis (Wardlaw and Porter, 1967). The proportion of photosynthate stored in the grain rises with the course of grain development up to about 50% with most of the rest being lost in respiration (Evans, 1968).

Grain filling is by no means wholly dependent on translocation of assimilates to the ear, since photosynthesis by the ear itself can provide about half of the required assimilates. The exact proportion depends on the presence or absence of awns, the light intensity and the stage of development of the ear which cause more glume area to be exposed as the grain fills (Buttrose, 1962), and because the leaves may yellow long before the ear does leading to a progressive rise in the proportion contributed by the ear (from 26% to 95%), Birecka, and Dakic-Wlodkowska (1963), cited by Evans (1968). Analysis of the data presented by Carr and Wardlaw (1965) suggests that the transport capacity of the culm could hardly support grain growth at even half maximal rates. Similarly, findings like that of Bingham (1967), where reduction of grain number per ear led to a small increase in individual grain weight could have been due to a limitation by the transport capacity of the culm rather than by the photosynthetic capacity of the leaves (Evans, 1968).

Consequently, the relationship between grain yield and particular yield components will vary greatly depending on the sequence of environmental conditions at the various stages in the development of the crop.

It seems logical then that the uncertainty surrounding the agronomist's yield predictions has two main components. One is due to his imperfect knowledge of the exact relationships between yield and the precise environmental circumstance. The second component emerges from his present incapability to forecast the environment both in space and in time with reasonable precision (Turrent, 1968).

It has been shown that the seasonal distribution of the weather factors (namely, precipitation, solar radiation, temperature and wind) has a very important economic significance for wheat production. The definition of the different physiological stages for the wheat crop in the area under study is considered a fundamental step toward the planning and development of methodologies in the assessment of the environmental effects on grain production.

Time and conditions which are required for the completion of the different phases of plant development determine the growing period of each plant. However, the rate at which these phases are completed depends entirely upon the complex of environmental conditions and the genetic make-up of the plant. Hence, considerable differences in the duration of the growth and development periods of different wheat varieties for a given area or for the same variety at different locations might be expected.

Nevertheless, an attempt to describe the mean duration of individual growth-development phases for two intermediate[1] wheat cultivars commonly sown in the area under study has been done by using the averages of observations throughout several years at the Barrow Experimental Farm and Balcarce Experimental Station.

On the basis of external morphological characteristics the life cycle of the wheat plant is commonly subdivided into five growth-development periods: seeding to emergence; emergence to tillering; tillering to booting; booting to heading (earing); and heading to maturity. Because of the importance of this last period in the yield determination, it is customarily subdivided into four stages; heading to flowering, flowering to milky stage, milky stage to dough stage, and dough stage to maturity.

From the data collected by Barrandeguy (1975) two curves representing the above mentioned growth-development stages are presented in Figures 1 and 2. Figure 1 attempts to

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[1]Wheat varieties are classified as winter wheats, intermediate wheats and spring wheats. This classification refers to their habits of growth, which are considered to be inherited characteristics (Nuttonson, 1955).

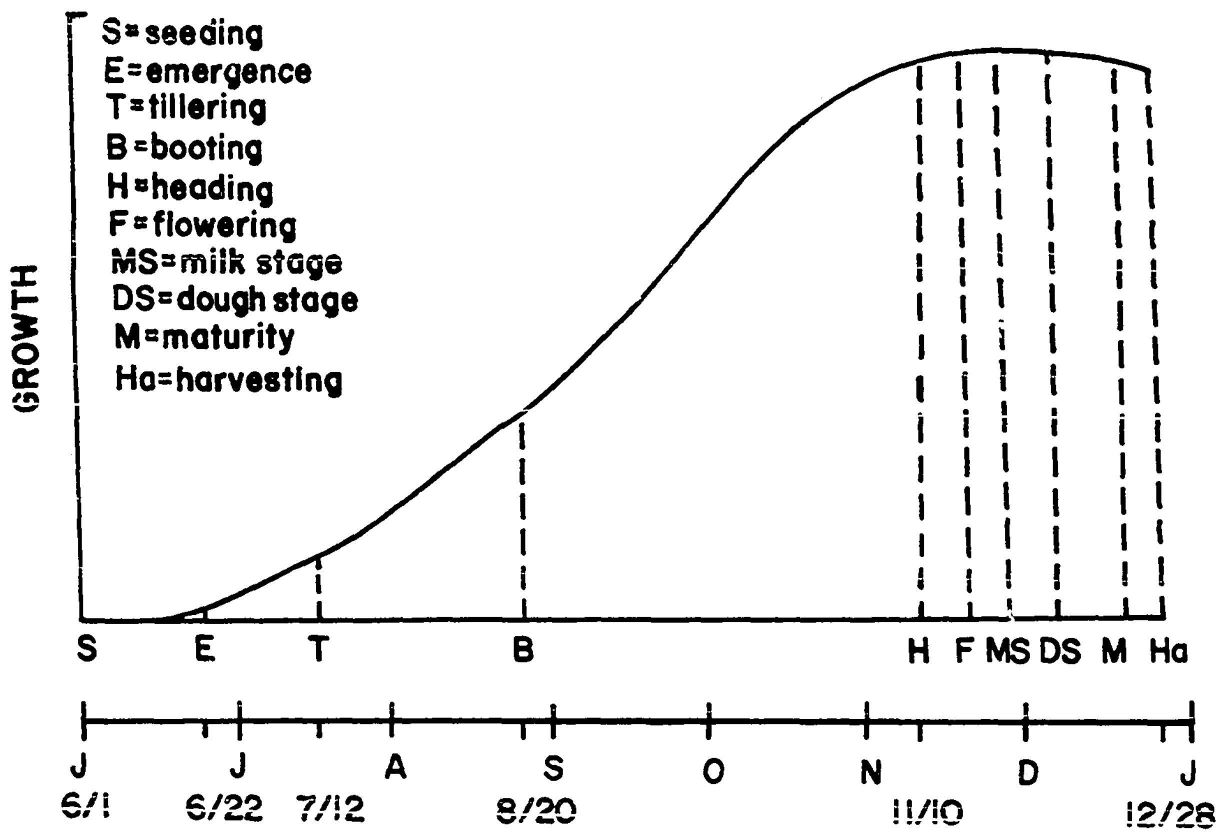


Figure 1. Growth and development stages in the life cycle of Buck Namuncura and Tacuari Inta (<u>Triticum aestivum</u> L.)

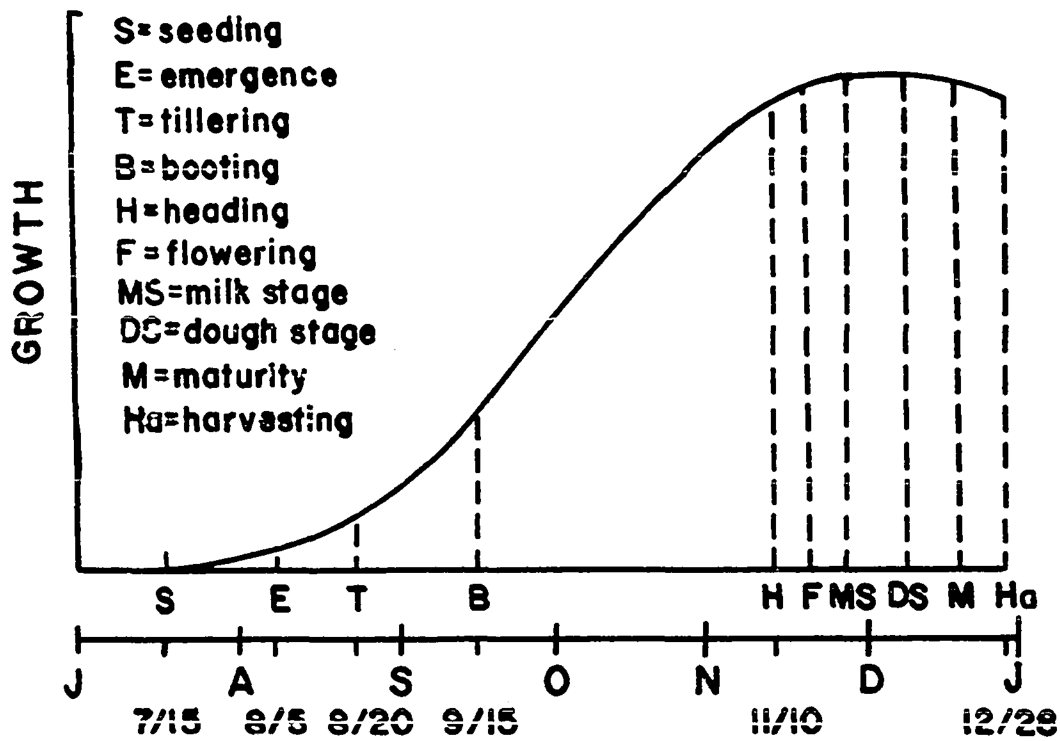


Figure 2. Growth and development stages in the life cycle of Marcos Juarez Inta and Taganrog Buck Balcarce (<u>Tritucum</u> <u>durum</u> L.)

represent the life-cycle for Buck Namuncurá (*Triticum aestivum*) and Tacuari Inta (*Triticum aestivum*) when sown in the area of Tres Arroyos County. Figure 2 represents the life-cycle for Marcos Juarez Inta (*T. aestivum*) and Tangarock Buck Balcarce (*T. durum*) sown in the same area.

Methods Used in the Evaluation and Assessment of the Response of Crops to Fertilization

Methodologies in field experimentation have drastically changed over the last 25 years. Before 1950 the effect of one experimental variable at different levels was generally studied while keeping all other factors at a constant level (Hutton, 1955).

As envisioned by Tejeda (1973) the early statistical methodology for design and analysis of experiments was probably directed to isolate the effect of the factor being investigated from the effect of those factors not susceptible of being controlled and/or held constant. The effect of non-experimental factors was then considered experimental error.

Dumenil and Nelson in 1948 emphasized that more detailed investigations, such as factorial fertilizer rate experiments, were necessary to provide information on interactions. Still, all factors other than the treatment variable were assumed to be constant.

A great deal of information relating yield and soil factors was collected during the fifties using the factorial treatment design from which simultaneous effects of two or more production factors were evaluated as well as their interactions. Response surfaces were derived from this information and economic rates of fertilizer application were calculated for a given soil association area (Baum, et al., 1957). The main limitation of the information obtained by this procedure was the heavy dependency upon the value of the rest of the production factors at the experimental site which in turn restricted the application and usefulness of the results for different environmental conditions.

In 1960 Collis-George and Davey suggested that since the influence of soil physical and micrometeorological factors was known to be of great significance in determining the biological response of plants, it would be appropriate to restrict the number of conventional field experiments and replace some of them with completely instrumented experiments. And they further stated "until complete descriptions of experiments are available the quantitative importance of environment and its interaction with fertilizer and cultivation practices cannot be determined."

During the sixties several strategies were postulated and developed in order to achieve a quantitative analysis of the relationships between the yield of a given crop and causal production factors.

Ferrari in 1965 postulated two different alternatives for the collection of the data, namely manipulative versus nonmanipulative experiments. In nonmanipulative experiments, the quantitative data is collected through observations and measurements of yields and factors under conditions within a network of observation sites distributed within fields in the area under study. The observation sites, generally farmer's fields, are selected in order to cover as far as possible, the complete range of variation that each of the factors under consideration may reach. However, this method has a strong drawback when the range covered by the levels of a factor does not reach an optimum (Culot, 1974). Indeed, the validity of the quantitative relationships derived for it and for the other associated factors is strongly biased in such a circumstance. On the other hand, in manipulative experiments, a network of standardized experiments has to be established using an appropriate experimental design and with a treatment combination selected on the knowledge that a few important factors would not reach the optimum level within the ecological and management condition of the area unless experimentally applied. The sites are selected to cover a wide range of levels for the other factors believed to be important which are quantified at each location. The whole set of data obtained in this way is then generally processed using multivariate analysis procedures in order to establish the yield-factor relationships which lead ultimately to a final yield function.

Furthermore, if some management factors, such as variety, sowing date, plant density and weed and pest control are thoroughly optimized better insight can be given to the influence of the uncontrolled environmental factors (Culot, 1974).

Selection of the experimental design

As mentioned before the selection of the appropriate experimental design and the choice of an adequate model to represent the data obtained are two fundamental steps in this process. So, some time will be devoted here to the analysis of these two points.

After the publication of Yates (1937) on procedures for analyzing factorial experiments, factorial arrangements of fertilizer treatments gradually became accepted as the most adequate determination of points within a factor space. Because complete factorials of orders higher than 5^2 (two factors at 5 different levels) or 3^3 often presented serious limitations to be located under field conditions in homogeneous soil areas due to the large number of plots for a single replication, other alternatives were studied and developed. Fractional factorials are one possibility in reducing the total number of treatments without affecting appreciably the precision of certain effects to be estimated. However, this approach is useful mainly for reducing factorial arrangements of the type, 2^2, where two levels of the factor are being studied. So, its applicability in this type of study, where more than two levels of a factor are needed to delineate the response curve, is disregarded.

Other alternatives were sought, and in 1957 Box and Wilson presented a design consisting of a carefully selected number of treatments only moderately greater than the number of effects to be estimated. Their composite design for three factors at three different levels (3^3) required only 15 instead of the 27 treatments required by the complete factorial. Several central composite designs and other incomplete factorials have been proposed (Box and Hunter, 1957; Box and Draper, 1963) to mention only a few, and it is not intended to describe those here.

Another approach to the selection of a design with fewer number of treatments than the complete factorials has been quoted by Cady and Laird (1973) as being used in recent years. They said that generally the investigator begins with a factorial arrangement and either systematically eliminates treatment combinations throughout the factor space, or as suggested by Pesek (1956), "discard treatments which are very likely to be outside the range of economic substitution". They proceeded further, "The number of possible partial factorials corresponding to any given complete factorial arrangement is large, and no objective criteria have been established to assure the selection of the most efficient design for the specific objective at hand". If the quadratic equation or second degree polynomial is selected to represent the data (either in its natural or in the square root scale) complete orthogonality among all possible comparisons (linear, quadratic and linear x linear interactions) are sought by some authors (Colwell, 1974). Others are less demanding, for example, Voss, Hanway and Fuller (1970), stated that "a certain amount of orthogonality of treatments is deemed desirable". They were more concerned with independence of the linear effects (which were planned to be used to correlate with the site variables).

Pesek (1974), felt that it is more desirable to increase the number of observations in such a way that all coefficients are estimated with about the same degree of confidence rather than estimating some coefficients more precisely than others.

Number of replications

After the investigator has decided what design and what treatment combination he is going to use the decision on the number of replications has to be made. If the treatment or input on each plot is considered to be made up of both applied fertilizer and the soil analysis values, there can no longer be replication in the true sense of the word. Hence, it seems that there is little advantage or disadvantage to replicating or not replicating a set of fertilizer treatment combinations at each site (Pesek, 1974).

However, having a replicated design permits an examination of the error mean square, that is, the replication by treatments interaction within each site. When this is compared with the mean square for deviations from the regression, one can judge how adequately the chosen regression fits the data. If the mean square for deviations from regression is significant, the investigator should examine the site variables in the experiment for a possible significant factor not being considered. In the few cases where the mean square for deviations from regression has been examined in relation to the replications by treatment and error terms; it has been found not to be significantly different (Pesek, 1956 and Tejeda, 1973). Nevertheless Cady and Laird (1973) pointed out that the magnitude of bias obtained in fertilization studies has been sufficiently large that a recommendation has been made in fertilizer use studies to select a treatment design to reduce bias and to control the error variance primarily through replication.

Selection of the model

Since the deterministic law that governs crop production is not known and since there is general recognition among researchers of the existence of unidentified stochastic components and errors of measurements (Kendall, 1972; Kempthorne, 1972), alternative strategies to develop statistical models which can provide a representation of the phenomenon being studied with a certain degree of confidence are generally employed. The quality of the model is judged on the basis of the agreement between partial measurements of the phenomenon and the corresponding values derived from the model (Tejeda, 1973).

The same author, (Tejeda, 1973), describes the model building problem as a four step process:

1. Selection of a family of functions to approximate the unknown form of the factor-yield relationship.
2. Identification of a subset of variables within the unknown set of factors and interactions functionally related to yield to be used to predict yield.

3. Estimation and testing of the properties with available data.
4. Validation of the final model.

Continuous models based on a specific mathematical equation are preferred over discrete ones because the precision with which the crop yields produced at different rates of fertilization may be substantially increased, and yield may be predicted for any levels of the input variables within the range of the employed treatments. The prediction equation provides also a convenient means for calculating the optimal rate of fertilization (Anderson, 1956). Restating the fact that the deterministic model of plant growth is not known, the researcher must accept the fact that the functional representation of his results will be in error or biased to the extent that his assumed model differs from the true model (Cady and Laird, 1973).

Johnson (1953), Hagin (1960), Tejeda (1966), Gandarillas (1970), Melsted and Peck (1977) and several others have done partial comparisons between groups of different functions used to estimate the factor-yield relationship.
Heady and Dillon (1961) have described the properties of the response surfaces generated by the most frequently used equations with two variables. These are the Cobb-Douglas, the Mitscherlich-Spillman, the resistance equation proposed by

Balkmukand, and the quadratic and square root transformation of the second degree polynomial.

Experience, experiments and intuition suggest that responses of crops to fertilizers should be characterized by diminishing returns at least over part of the range of responses (Pesek, 1974). According to Heady and Dillon (1961) all the equations reviewed provided for the possibility of diminishing returns. However, only the quadratic equation and the square root transformation of the second degree polynomial provide for positive and negative response to additional increments in the same function. Likewise, only these two forms of equations (the two polynomials) provide for a unique combination of two factors to produce a maximum yield or yield response. Tejeda (1966), Cady and Laird (1973) and Pesek (1974) agreed on the arguments in favor of the second degree polynomial on these three bases: it is easy to manipulate algebraically; its parameters are linear combinations of the observations and may be readily estimated using least squares procedures; and it can be easily manipulated in economic analysis. Despite this agreement there is some evidence indicating that the quadratic polynomial may be inadequate particularly when used in economic analysis and management decisions (Tejeda, 1966, 1973; Johnson, 1953).

Colwell (1974) preferred the square root transformation of the second order polynomial over the natural scale because it gives a more realistic response form with low curvature in the vicinity of the maximum yield. Cady and Laird (1973) pointed out that when using the square root transformation of the second degree polynomial for values of '$\underline{x}$' greater than one, the slope of the square root function changes more slowly than the natural scale. Thus the square root function has a larger slope than the quadratic at low levels of input and becomes much flatter than the quadratic at high input levels.

Heady and Dillon (1961), after fitting the same set of data to the quadratic and the square root functions, concluded that the square root function represented the expermental observations somewhat more closely than the quadratic equation. However, differences in the size of the coefficients were small.

What Tejeda (1973) refers to as step number 2 in the model building process, is known in statistics as inference for incompletely specified models (Bancroft, 1965), which implies that at least some knowledge about which variables should be in the model is available to the researcher. This knowledge may come from the substantive field theory or results from previous investigations. Kennedy and Bancroft (1971) stated that such previous knowledge should be enough to formulate these three basic assumptions:

a. The model should include at least a "basic subset" of r independent variables.

b. Uncertainty exists as to whether or not some or all of the variables from a subset containing (k-r) independent variables should be included in the model (k greater than r).

c. The relative order of importance of the (k-r) dubious variables with respect to the dependent variable is known, with x_{r+1} being the most important, and x_k the least important.

The problem of determining an appropriate equation based on a subset of the original set of variables contains three basic ingredients; the computational technique used to provide the information for the analysis; the criterion used to analyze the variables and select the best subset if that is appropriate, and the estimation of the coefficients in the final equation (Hocking, 1976).

Some available procedures like the stepwise regression methods described by Draper and Smith (1966) might embrace the three ideas without clearly identifying them.

Following the idea of Kennedy and Bancroft (1971) and assuming we are after the factors which affect the response of wheat yields to N and P fertilization at different sites, the alternatives in the model building process can be delineated as follows.

It will be assumed here that the second degree polynomial has been selected to represent the factor-yield relationship at each site and that "n" experimental sites are available. If nitrogen and phosphorus as fertilizer treatments are applied, at least those two variables have to be considered in the model to explain the factor-yield relationship. Hence, the first step is to fit a second degree polynomial at each site relating yield to the applied doses of N and P. The model then would be:

$$Y = B_o + B_1N + B_2P + B_3N^2 + B_4P^2 + B_5NP + e$$

where

Y = yield (the amount of wheat grain produced),

N = the actual amount of nitrogen applied (in kg/ha),

P = the actual amount of phosphorus applied (in kg/ha),

B_o = the expected yield without fertilization, that is, the yield produced by the uncontrolled factors alone,

$B_1, B_2, \ldots B_5$ are the parameters which quantify the response of the wheat crop to the application of N and P fertilizers, and e = the random error component, i.e., the amount by which any observation is expected to differ from the value predicted by the regression equation.

This fitting can be done by multiple regression technique using ordinary least squares procedures for the estimation of each parameter (Draper and Smith, 1966).

Then, for a given site "t", the following equation will be obtained:

$$\hat{Y}_t = b_{o_t} + b_{1_t}N + b_{2_t}P + b_{3_t}N^2 + b_{4_t}P^2 + b_{5_t}NP.$$

In this equation the six estimated regression coefficients ($b_{o_t} \ldots b_{5_t}$) will attempt to explain the nonrandom variability at site "t". If the same treatment combinations are used and if there were no other factors affecting the yield, or if the uncontrolled factors were identical for each site the coefficients will be identical for the n sites analyzed, i.e., the response to fertilization will be equal at all sites. But this situation is found very seldom in biological systems. The next step is to test for the homogeneity of the regression coefficients across the n sites. Since the regression coefficients are random variables with a conditional multinormal distribution (Johnston, 1963), an F-test is suitable for this comparison (Cady and Fuller, 1970).

The hypothesis to be tested is $B_{o_t} = B_o$ for all values of t; t = 1,2,...n sites or in other words "all the b_{o_t} are estimating the same parameter and all the uncontrolled factors have no effect on the mean yield at site t, i.e., the main effect of all the uncontrolled variables is zero" (Cady, 1974). The F-test is used,

$$F = \frac{\sum_{t=1}^{n} (b_{o_t} - \bar{b}_o)^2 / n-1}{C_{oo} S^2}$$

where

$\bar{b}_o$ is the mean of the b_{o_t} across the n sites,

S^2 is the estimated experimental error from pooling the individual site's experimental error, and

C_{oo} is the first diagonal element from the inverse of the matrix of sum of squares and cross products obtained from the treatment combinations.

The same argument holds for all B_{i_t}, i = 0,1,2,...5. For example, if all the b_1 are estimating a single B_1 the linear effect of applied nitrogen will be the same at all sites and no interaction will exist between applied nitrogen and the uncontrolled site variables.

The F-test for the homogeneity of the mean and linear terms will be significant almost always, so the next step is to identify those measured site or uncontrolled variables associated with the significant F-values (Cady, 1974). Several techniques have been proposed to accomplish this task.

Voss and Pesek (1965) indicated that simple linear correlations between each regression coefficient and the measured site variables or uncontrolled factors should be done to find which uncontrolled variables are associated with the yield and response to fertilizers across sites. However, it was emphasized by the authors that the biological explanation for such relationships must still be logically deduced. Basic soil fertility knowledge can be used to indicate those site variables that undoubtedly are important (Cady, 1974). Also all simple linear correlations between pairs of uncontrolled variables can be calculated to appreciate the degree of collinearity between site variables.

Nevertheless some problems have been reported in the use of this procedure. Culot (1974), after using the method proposed by Voss and Pesek (1965), concluded that "the selection procedure was not completely satisfactory as it would induce the discarding of some important factors having a nonlinear relationship with the regression coefficients". He further stated that plotting the data on graphs showed that in many cases the relationship was curvilinear sometimes with asymtotic tendency. So, he recommended that the first selection of variables to be included in the full model has to be done using a combination of statistical and graphical procedures.

Voss (1969), Tejeda (1973), Cady (1974), and Estrella et al. (1975) recommended that each of the b_{it} obtained can be regressed on the corresponding site variables.

For example:

$$b_{0t} = \alpha_{00} + \alpha_{01}X_{1t} + \dots \alpha_{0p}X_{pt} + e_{0t}$$

where the α_{0j}, j = 0,1,...p, are the parameters relating the estimated site means to the p uncontrolled variables and e_{0t} is a random error component.

Estimating the α_{0j} has some of the same problems as previously mentioned, namely that of multicollinearity among the X's. As postulated by Cady (1974), "Two kinds of X usually can be identified, (a) factors with sufficient ranges to almost always affect the regression coefficients, and (b) factors with ranges that might or might not affect the regression coefficients, depending on the sampling in the given series of experiments." Factors of type (a) should definitely remain in the model and the parameters estimated by least squares. With factors of type (b) a criterion such as the residual sum of squares, or a function of the residual sum of squares such as R^2 or the C_p statistic (Mallows, 1973), or the prediction sum of squares "PRESS" (Allen, 1971) should be used for a decision on inclusion or exclusion of the variables.

Validation of the model

The prediction of a future response and the estimation of the mean response for a given input are the two generally adopted criteria in the validation of the model. A brief description of each one is considered important at this point. In the first case the prediction equation is intended to be used as a transfer vehicle, that is, a new different, but similar set of data can be fitted to the selected model to predict yield at any site within the defined population. In the second case, the objective is to develop a model for the response as a function of the observed inputs and various functions of these inputs. Thus, a good agreement between the predicted yields ($\hat{Y}_t$) and the observed yields (Y_t) at any site within the explored area is sought.

The important issue here is that the variance of the estimate of the mean response is given by:

$$VAR\ (x'\hat{B}) = \sigma^2 x'(X'X)^{-1}x \qquad (1)$$

where

x' represents a particular vector of input variables,

$x' = (x_1, \ldots x_i)$,

$\hat{B}$ = the least squares estimate of B (the vector of the unknown regression coefficients),

σ^2 = the residual mean square, and

$(x'X)^{-1}$ = the inverse of the matrix of sum of squares and cross products formed from the x' vector.

While in the first case the prediction variance is given by:

$$VAR(\hat{y}) = \sigma^2(1+x'(X'X)^{-1}x) \tag{2}$$

where

$$\hat{y} = x'\hat{B} \ .$$

It is then clear that in the case of prediction (first case), the contribution to the prediction variance due to the variability in estimating the coefficients, namely Equation (1), may be small relative to the inherent variability of the system being studied (Hocking, 1976).

The danger of extrapolating beyond the range of the data used to develop the estimates is apparent since the current model may no longer apply. However, even if the model is appropriate, a predictor which is adequate within the experimental range may be very poor outside of this region because of poor parameter estimates resulting from near degeneracy of the X matrix (Mason et al., 1975).

The residual sum of squares for deviations from regression, $\Sigma(Y-\hat{Y})^2$, is a measure of the failure of a regression equation to correctly predict the same set of yield values used in estimating the regression coefficients for the model. Since the residual sum of squares is lowered, in practice, with each additional variable which entered the model, full models will generally present lower values of $\Sigma(Y-\hat{Y})^2$ than reduced ones. However, the addition of a variable to the prediction equation almost always increases (and never decreases) the variance of a predicted response (Walls and Week, 1969). An ideal procedure then would include variables important in reducing bias without adding those that will unnecessarily increase the variance of a predicted value (Cady and Allen, 1972).

If prediction is the major objective, then the validation of the model with a new set of similar data is the key point. But in most of the cases the agronomist does not have an additional set of data, collected under comparable conditions, ready to be used in the assessment of the selected model; hence the splitting of the available data into two groups, one for analysis (e.g., selection of the variables and estimation of the coefficients) and another for assessment, has been proposed (Laird and Cady, 1969). The basic idea behind the partition of the data is that the data used for the selection of the variables and establishment of the model should not be used in the validation procedure.

The question of how to partition the data and the decision as to whether this luxury can be afforded has led several investigators to consider integrating the two concepts of analysis and assessment (Hocking, 1976).

If all but the ith observation are used to obtain a prediction term of Y_i say $\hat{Y}_p$ then an assessment function proposed by Allen (1971) is the sum of squares of differences between the observed and predicted values. Allen has named the function PRESS, that is,

$$\text{PRESS} = \sum_{i=1}^{n} (Y_i - \hat{Y}_p)^2$$

Cady and Allen (1972), claim that PRESS is especially efficient in weighing the goodness of a particular potential variable to predict observations not included in the estimation of the model parameters.

However, when the same set of data was analyzed using PRESS and a forward elimination technique (stepwise), the residual mean square attained by PRESS was 10% higher than the stepwise. Most of the variables selected by PRESS were also selected by the stepwise procedure. In fact the ordering of the first few variables was the same for the two techniques. The main difference found, was in the cut-off point, that is the PRESS procedure selected a smaller subset of predictor variables than stepwise. The future prediction sum of squares (as defined above) using the PRESS criterion was 30% lower than the stepwise.

CHAPTER III. MATERIALS AND METHODS

Physical Description of the Area Under Study

The area under study is located in the southeastern part of the Buenos Aires province between 37°40' and 39° South Latitude and the meridians 57°30' and 62° West. It can be defined as a generally flat area (slopes generally vary between 0.5-2.0%) with some landscape discontinuities like the Tandilia Hills and the Ventana Hill system. The soils belong to the order Mollisols and the predominant sub-orders are Udolls, Albolls and Aquolls. The parent material is generally loess but some of the intrazonal soils (Natralbolls and/or Natraquolls) have been developed from alluvium. The organic matter content in the surface horizon varies from 6.5% in the east to 1.5% in the west according to the annual average rainfall. A similar variation is observed in the clay content of the B horizon which goes down from 48% in the east to 18% in the west. Generally speaking there is a gradual increase in the development of the B horizon from West to East.

Annual rainfall averages 800 mm in the east boundaries of the region and gradually diminishes to 600 mm in the southwest boundary. The amount of precipitation within the growing season of wheat (sowing to physiological maturity) varies from 250 mm in the west to 400 mm in the east, but considerable variations are recorded among years. Potential evaporation (tank A) for the growing season averages 668 mm for the western part and 409 mm for the eastern area. Temperature variations are not very pronounced. In fact, the monthly average temperature during the coldest month of July varies by only one degree from 8°C in the east to 7°C in the west. The mean annual temperature averages 14°C throughout the area with an average of 20°C for the hottest month of January. However, monthly average temperatures during the last three months of the growing season are 2°C higher in the western than in the eastern part.

Most of the soils devoted to wheat production do not present any serious impediments to root penetration and development and have a good water storage capacity (200 mm for the first meter). Some series associated with the major sub-group have a solid impermeable layer of $CaCO_3$ at different depths which vary widely within the landscape. The thickness of the impermeable layer also varies with topography, but whenever it occurs above a meter in depth, it constitutes a major constraint for root development and water storage. Investigations conducted thus far show that a considerable part of the area under study has small amounts of available soil phosphorus in the surface horizon. Most of the soils have values of total P in the range of 500 ppm, but 75% of this amount is in the organic form (Culot and Bolaño, 1967). A fractionation study done by the same investigators demonstrated that on the average, for a soil pH of 5.8, 43% of the mineral P is linked to Ca 35% is linked to Al and 22% is linked to Fe.

Several investigations, conducted in the area using greenhouse and field experiments, have proven the response of several crops (wheat, potatoes, pastures) to P fertilization (Garay, 1968; Garay et al., 1969; Darwich, 1968; Berardo and Darwich, 1972, 1974).

After the work of Culot and Bolaño (1967) in which five different availability indicators for P were assayed (Bray and Kurtz; Bray II, Olsen, Egner and Truog), the method described by Bray and Kurtz (1945) was adopted as the most suitable one. Nevertheless correlation procedures, testing the five methods against a large number of samples from different experimental sites, were never accomplished. Tuñon and Darwich, 1971, and Berardo and Darwich, 1974, have correlated yield responses of wheat and pastures from fertilizer trials with the amount of available P measured by the Bray and Kurtz method in an attempt to identify the so-called "critical level". Twenty-three different sites over a two year period were analyzed in the first case and sixteen over a three years period in the second case. The critical level was determined using the method proposed by Cate and Nelson (1965) and in both cases the value found was about 7.5 ppm for the wheat crop.

In the work of Berardo and Darwich (1974) an economic analysis was performed using discrete doses of fertilizers. It was found that 65% of all the fields had values of P below the critical level and produced economic returns due to P fertilizations. Only 25% of the trials produced economic returns due to nitrogen fertilization. The interaction of NxP was positive in 73% of the cases. Several laboratory studies have been done in an attempt to find a biochemical and/or chemical availability index for N (Navarro, 1966, 1968; Freitas, 1973). Correlations with yield responses have been attempted using sixteen different experimental sites over a three year period (Berardo and Darwich, 1974). No significant association was found between levels of total nitrogen or initial nitrate at seeding time and the yield response of wheat to N fertilization. Navarro (1966) concluded that the nitrification potential index, as described by Stanford and Hanway (1955) with some modifications, can be used satisfactorily to predict N availability for the plants. He correlated total N and NO_3-produced by incubation with yield increments produced by N fertilization and found that the incubation technique gave the best results. Nevertheless the number of samples used in this study were considered insufficient by the author to produce reliable estimations.

More recently, Berardo et al. (1975) have used new indexes in the search of a diagnostic method for N fertilization. They analyzed yield responses to nitrogen fertilization from 61 experiments located throughout the wheat area during the three year period of 1972-1975, and found that the increases in grain production due to N fertilization amounted to more than 300 kg/ha in 25% of the cases. They also stated that the response to N was concentrated in the coastal area where the soils have coarser textures and during years of higher precipitation. The indexes which they used were; the organic matter content of the surface horizon, the amount of nitrates present in the soil at seeding and tillering time at two different depths of 0-20 and 0-50 cm, the potential nitrification index as described by Navarro (1966) and the amount of nitrate in plants at tillering time extracted by a 0.025 m solution of aluminum sulfate and measured by a nitrate-electrode as suggested by Cantliffe et al. (1970). They regressed these variables and other uncontrolled variables which might affect their behavior such as rainfall at different periods of the growing season, water stress, %

clay in the B horizon and number of years without legumes on the yield increments obtained with a certain N application (the one which produced the highest yield). Using a step-wise technique they concluded that the amount of nitrates in plants at tillering time was the variable which presented the highest association with the yield increases due to nitrogen fertilization. By regressing the amount of nitrates in plants at tillering time with the relative maximum yield (yield of the check plot/maximum yield attained with any dose of N. x 100), they were able to explain up to 83% of the variation in yield observed in the experiments located on the coastal area. However, this variable explained only 36% of the yield variation when all the sites throughout the area were included.

The amount of nitrates present at seeding time from 0 to 50 cm was also regressed on the direct yield increments ($Y_N - Y_{Check}$). An R^2 of .57 was obtained for the trials in the coastal area, but it decreased to .33 when all the sites were included.

The amount of exchangeable potassium in the soils throughout the area is considered very high with average values ranging between 1.50 and 3.00 meq/100 gr of soil for the surface horizon. This high value could be associated with the mineral components of the parent material which are rich in K. Early field experiments conducted throughout the region using K fertilizers have never shown any significant response to K fertilization (Garay et al., 1969).

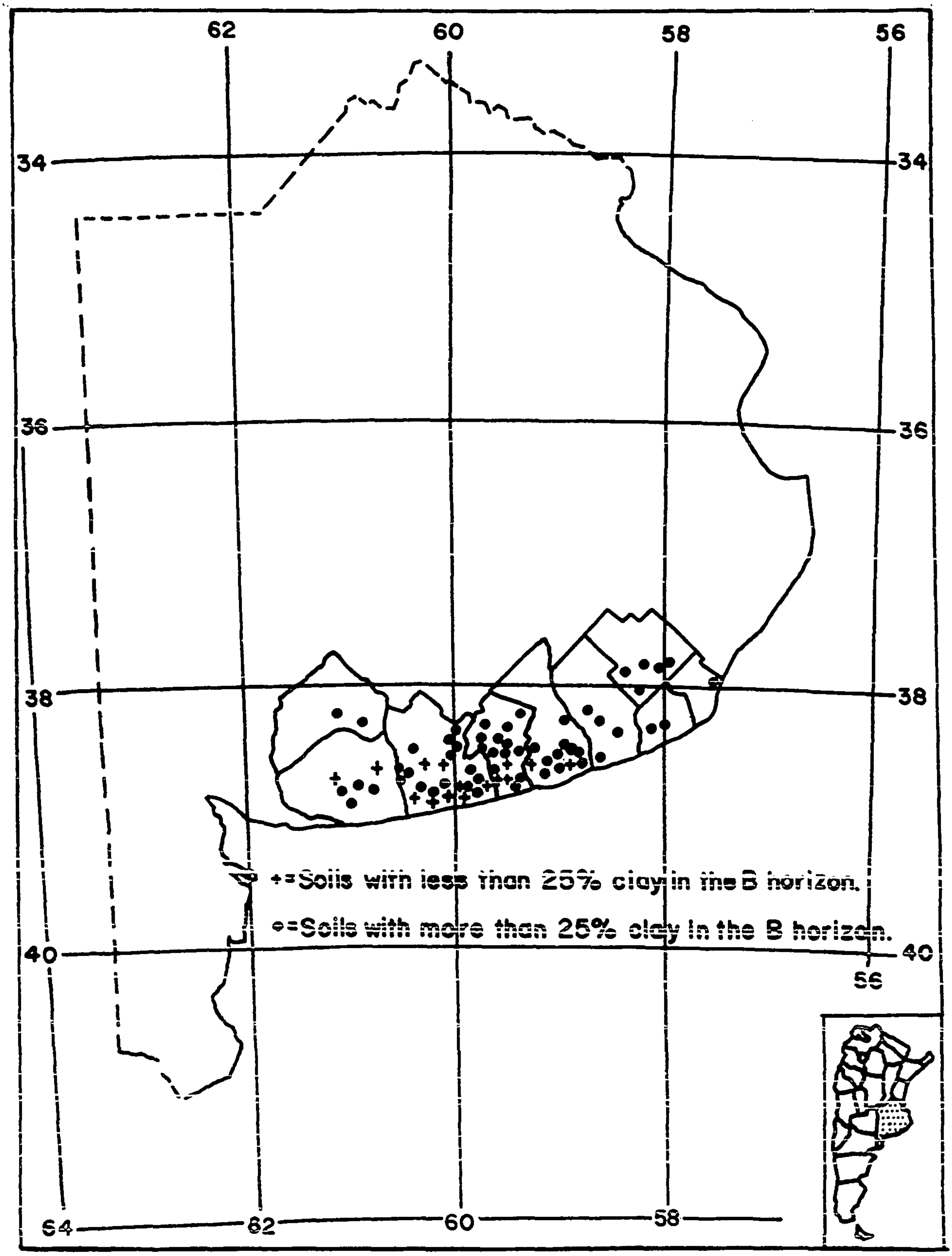
Almost all the soils devoted to wheat production are moderate to well-drained with the exception of some Aquic Arguidolls or Aquic Hapludolls which are commonly present in small closed areas associated with some specific landscape configurations.

Location of the Experimental Sites

Using the available information regarding soils, climate, and cropping conditions 15 multifactorial experiments were designed and implemented throughout the area in 1972, 42 in 1973 and 15 in 1974. The approximate location of each experimental site is given in Figure 3. The explored area encompassed about 3.3 million ha and could be visualized as a rectangle which extends 330 km in NE-SW direction along the Atlantic coast and about 100 km inland in S-N direction.

The name of the representative soil pedon at each site is given in the Appendix.

Figure 3. Location of experimental trials within the area of study

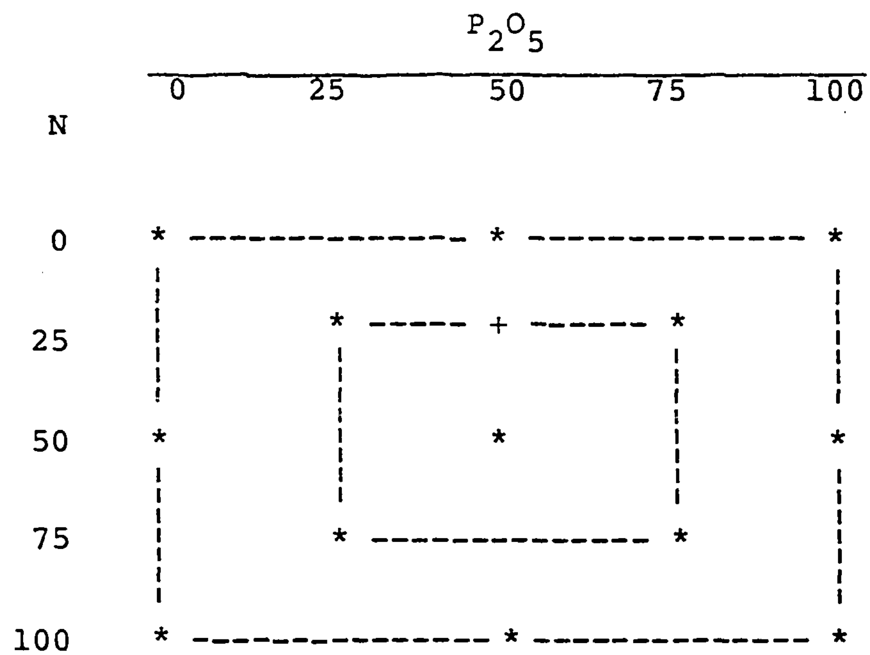

62
60
58
56
34
34
36
36
38
38
+=Soils with less than 25% clay in the B horizon.
•=Soils with more than 25% clay in the B horizon.
40
40
56
64
62
60
58

Experimental Design and Treatment Combinations

For the first year of experimentation, 1972, an incomplete factorial 5^2 was chosen. This design is generally known as a double square and is a modification of the second order central composite design for two variables (Cochran and Cox, 1957). All the points along each variable axis are equally spaced and an outer square was added with the coordinates of ± 2, ± 2. An additional treatment combination was added near the point estimated as the more likely economic optimum combination from previous investigations. This treatment was included in an attempt to increase the precision of the estimation around this critical point. Thus, the number of treatment combinations was increased from 13 to 14. The actual doses of N and P are given in Figure 4.

This design was selected to obtain ample coverage in the range of the applied variables while keeping the number of treatment combinations small and maintaining adequate increments among sequential doses.

This design presents one problem and it is the fact that the quadratic terms estimated by the regression model using this design configuration are not independent. Only the linear and linear x linear (interactions) terms are orthogonals. So, after the first year of experimentation, it was decided to replace the treatment design by a 4^2



* = selected treatments in the double square design configuration

\+ = additional treatment added

N and P_2O_5 are expressed in kg/ha

Figure 4. Selected treatment combinations for 1972

complete factorial with doses of 0, 30, 60 and 90 kg/ha for N and P_2O_5, respectively. The sites were selected in a way to properly cover the variation of the site factors within a desired range. Heavier weight was given to Tres Arroyos County in the selection of the sites because of the variability of the soils and the importance of wheat in this area. Management conditions infrequent in the area such as fallow periods shorter than 1 month were avoided. In each site the blocks were located in such a way as to avoid slope influences or to avoid any detectable uncontrolled variation within each block.

At each site the 14 or 16 resulting treatments were replicated twice, each time in a randomized complete block configuration. Each block included 14 treatments in 1972 and 16 treatments during 1973-74.

At each plot wheat was seeded in 17.5 cm spaced rows using a John Deere drilling machine with fertilizer box attachment. The plot size was twice the operational width of the driller, 36 rows (6.30 m) by 60 m in length. The seeding rates were adapted to each area according to former local experience: 240 pl/m^2 was used for the drier area of Cnel. Pringles and Cnel. Dorrego Counties, 260 for Tres Arroyos County, 280 for San Cayetano County, 300 for Necochea and 320 pl/m^2 for Balcarce, Loberia, Gral. Alvarado and Gral.

Pueyrredon Counties.

The fertilizers used were concentrated superphosphate (0-46-0) and urea (46-0-0). The wheat varieties employed are considered spring type varieties, generally adapted to high levels of fertilization. Tacuari Inta and Marcos Juarez Inta were used throughout the area during the three year period. The superphosphate was drilled with the seed at sowing and the urea was applied in split dressings, with one application immediately after sowing (leaving the tubes of the driller out of the disk) and with the second half applied at tillering time by hand dressing.

At harvest the outside two rows of each plot were discarded to avoid border effects, and the central part of each plot was harvested with a combine provided by the farmers. The plot results should thus represent the effects of fertilizers on commercial wheat crops.

Since the trials were surrounded by the farmers' wheat crop, the weed and pest control was done by the farmer. Information regarding previous crops and management of the field were collected at each site. The number of years since the last legume crop is intended to be used as a management factor along with the length of the fallow period and the degree of weed infestation, which was recorded on an arbitrary scale from 0-5. More details about the employed scale are given in the Appendix.

Field Investigations

At seeding time

Composite soil samples from 0 to 20 cm in depth were taken to represent the surface plough layer of each block at each site before sowing. Also, deep samples between 20 and 50 cm were taken in each block at each site during 1973 and 1974. A pit was dug between the two blocks in order to describe the soil profile, and samples were collected from each horizon for further analysis and characterization.

Rain gauges were installed at the sites where the farmer did not have an appropriate one, and the rainfall was recorded throughout the crop cycle by the cooperating farmer at each location.

At tillering time

Before the second application of nitrogen, soil samples were collected from the plots in each block with the higher doses of P and no nitrogen at depths of 0-20 and 20-50 cm. Also, from the same plots, plants were collected to determine the amount of total N and NO_3- present in the plant tissues. Holes were drilled in the center of the plots containing the higher combinations of N and P, and cylindrical gypsum blocks containing concentric electrodes (Shearer, 1963) were placed at depths of 15, 30, and 45 cm in order to monitor the variation of soil moisture between heading and physiological maturity.

Since it has been shown that no detectable growth occurs in many crops at the 5 bar suction level (Peters, 1957; Owen, 1958; Kemper et al., 1961; Perrier et al., 1961) and that field experiments on barley, corn, sugar beets, rye grass, alfalfa and potatoes have indicated that plant productivity is maintained for soil suctions which do not exceed 3 bars (De Backer and Boersma, 1968; Taylor, 1952), this value was considered to be the threshold level to determine if the soil had enough moisture to adequately meet the optimum plant demand for water. Readings of the electrical conductivity from each gypsum block were taken each week from heading to dough stage.

At harvesting time

The amount of grain harvested from each plot was weighed and samples were taken to determine the moisture content of the grain and other commercial indexes.

Laboratory Determinations

Physical

The moisture content of the grain samples collected from the different plots was analyzed using a conventional grain moisture meter. All the plot-yield values were then adjusted to 14% moisture and converted to kg per ha.

Monitoring soil water availability to plants Since different soils have different water-content water-tension curves, and since the equilibrium between a gypsum block and the adjacent soil is a water-tension and not a water-content equilibrium, the calibration of a gypsum block for water tension is considered more reasonable and more useful than calibration for water content (Gardner, 1965).

Calibration curves for water tension may be easily carried out using ceramic plate cells in a pressure plate extractor with a special pass-through for the electrical wires. The blocks are embedded in soil and placed on a porous plate or pressure membrane extractor constructed to accept pressures up to 15 bars. A special outlet on the cylinder wall allows nine separate electrical leads through the chamber wall. In this way the blocks can be connected to a meter and the electrical conductivity recorded at different tensions.

The calibration curve shown in Figure 5 was attained in

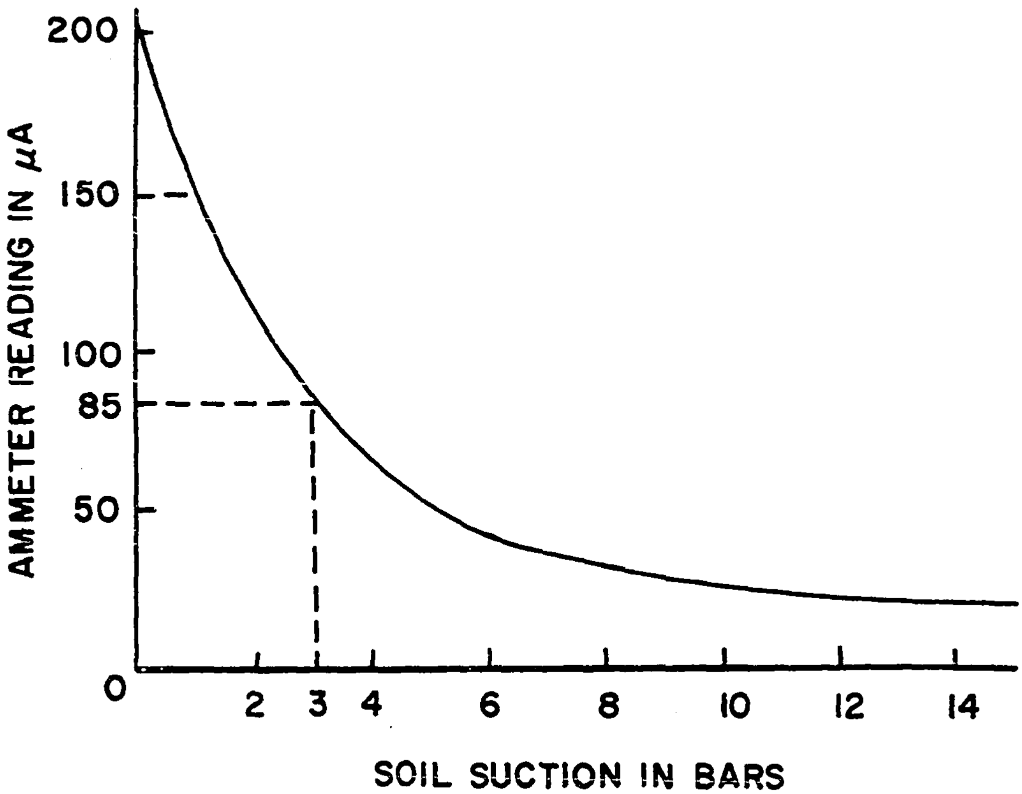


Figure 5. Calibration curve for the electrical moisture measuring blocks

this way. Since a meter reading of 85 μA corresponded approximately to a soil suction of 3 bars, as shown in Figure 5, this value was chosen as the threshold indicator for water stress. Any reading lower than 85 μA was considered stress. The total amount of rainfall recorded during the growing season was divided into four periods, in order to assess the importance of precipitation at different stages of the wheat crop, and its relation to other site variables. The chosen periods were as follows:

R1 = rainfall from seeding to tillering;

R2 = rainfall from tillering to booting;

R3 = rainfall from booting to milky stage;

R4 = rainfall from milky stage to maturity.

Soil structure was considered as one of the possible factors associated with the response of wheat to chemical fertilization. The stability of the soil aggregates was analyzed by the wet sieving technique as described by De Leenheer and De Boodt (1954). The results are expressed as the change in the mean weight-diameter of the aggregates caused by the wet-sieving. Hence, the higher the index value the less stable are the aggregates.

The percentage of clay in the surface and B horizon was determined using the pipette method (Day, 1965).

Chemical

Soil pH was measured by using a glass electrode in a soil water suspension with a soil to water ratio of 1:2.5. Cation exchange capacity was determined by using the method of ammonium saturation (Chapman, 1965). Organic matter content was calculated using the Walkley and Black procedure (Allison, 1965). Total nitrogen was measured by the regular macro-Kjeldahl technique as described by Bremner (1965).

To evaluate the nitrification potential of the soil the incubation technique proposed by Stanford and Hanway (1955) was performed with the modifications proposed by Navarro (1966). Those modifications consisted of the substitution of vermiculite for coarse sand (0.84-2mm) which was mixed with the soil in the incubation tubes in a ratio of 10 gr of soil to 30 gr of sand (air dried). Also, portions of fine and coarse sand were placed at the bottom and top of the incubation tubes. The incubation period was 2 weeks at a constant temperature of 35°C in a humid chamber. The initial nitrates present in the samples were leached out with water and recovered in a glass tube for further determination. The samples were then exposed to a suction of 0.33 bars for 10 minutes to eliminate excess water. The nitrates recovered in the glass tubes were measured, using an Orion 404 meter with a selective NO_3^- electrode (92-07) and a reference electrode (90-02).

The nitrification potential was determined only for samples of the surface horizon. The initial nitrates in the samples belonging to the second depth (20-50 cm) were extracted with water using a ratio of 60 ml of water to 10 gr of soil. The soil water solution was shaken for 30 minutes in plastic containers. After allowing for decantation the nitrates in the supernatant solution were measured using a selective NO_3^- electrode. The amount of NO_3^- between 0 and 50 cm was calculated as follows:

$$NO_3^-(0\text{-}50\ cm) = \frac{[NO_3^-(0\text{-}20cm)]20 + [NO_3^-(20\text{-}50cm)]30}{50}$$

Total nitrogen in the plant tissues was measured by using the micro-Kjeldahl digestion method (Bremner, 1965). Nitrates in plants were analyzed by using the technique proposed by Cantliffe et al. (1970). Available P was measured using the Bray and Kurtz procedure (Bray and Kurtz, 1945).

Exchangeable K was extracted with 1.0 N ammonium acetate solution and measured by a flame photometer, as described by Pratt (1965).

Statistical Analysis and Model Building

Since the original yield values for each replication were not available, all the analyses were done using the average plot yields from two replications for each treatment combination at each site.

The yield data from each site were then fitted to a second degree polynomial equation in the natural and square root scale using multiple regression techniques.

The respective equations for a given site "t" can be written as follows:

$$\hat{Y} = b_{0_t} + b_{1_t} N + b_{2_t} N^2 + b_{3_t} P + b_{y_t} P^2 + b_{5_t} NP + \varepsilon_t \qquad (1)$$

$$\hat{Y} = b_{0_t} + b_{1_t} N^{0.5} + b_{2_t} N + b_{3_t} P^{0.5} + b_{y_t} P + b_{5_t} N^{0.5} P^{0.5} + \varepsilon_t \qquad (2)$$

where

$\hat{Y}$ is the estimated yield (kg of wheat grain per ha),

b_0, b_1, b_2, b_3, b_4 and b_5 are the regression coefficient estimated by ordinary least squares procedures, while N and P are the actual doses of nitrogen and P_2O_5 applied to each plot. The element ε is the error term or the amount by which any observation is expected to differ from the value predicted by the regression equation.

In Equation (1): The value of the coefficient, b_{0_t}, represents the estimated yield without fertilization, that is, the yield generated by the uncontrolled factors at site t. The coefficient, b_{1_t}, represents the linear effect of applied nitrogen on yield at site t. It is the slope of the yield function at the origin (zero level of applied N and P) measured in the plane of the nitrogen axis. It is then the predicted increase in yield per each kilogram of applied nitrogen at this point. The coefficient b_{2_t} represents the quadratic effect of applied nitrogen at site t. It is a measure of the tendency of the yield function to deviate from a straight line in the plane of the nitrogen axis. Negative values for this coefficient mean that the function curves downward. (The larger the absolute value of b_2 the greater will be the curvature away from the straight line.) A negative b_2 indicates a decline in the rate of increase in yield as the level of nitrogen fertilizer increases.

The coefficients, b_{3_t} and b_{4_t} represent the linear and quadratic effects of applied phosphorus at site t. They represent values comparable to the linear and quadratic effects of nitrogen, except that they are measured in the plane of the phosphorus axis.

The coefficient b_{5_t}, represents the effect of the interaction between applied nitrogen and phosphorus at site t.

It is a measure of the extent to which the increase in yield from applied nitrogen or phosphorus differs when applied alone or in combination with the other. A positive b_5 coefficient means that the increase in yield due to a given increment of either of the elements becomes progressively larger as the level of the other nutrient is increased. Then the magnitude of the interaction coefficient is a measure of how much the response to one nutrient is affected by the amount of the other nutrient present in the soil (Laird et al., 1969).

The six estimated regression coefficients attempt to explain the nonrandom variability at site "t". If there were no other factors affecting yield, the same response would be observed at each site, for example, the parameters B_{0_t}, $B_{1_t}, \ldots B_{5_t}$ for all the sites t = 1,2,...n, will be identical so the b_{0_t}, $b_{1_t}, \ldots b_{5_t}$ are estimating the same parameter. This means that the uncontrolled factors have no effect on yield or on the response to fertilization at a given site "t", (t = 1,2,...n), i.e., the main effect of all the uncontrolled variables is zero.

This hypothesis was tested with an F-test as proposed by Cady (1974);

$$F = \frac{\sum_{t=1}^{n} (b_{0_t} - \bar{b}_0)^2 / n-1}{C_{00} S^2} .$$

Where $\overline{b}_0$ is the mean of the b_{0_t}, S^2 is the estimated experimental error from pooling the individual site experimental errors, and C_{oo} is the first diagonal element from the inverse of the matrix of sums of squares and cross products formed from the applied fertility variables (N and P treatments). Since there were three different experimental matrices, this test was performed for three separate groups of experiments.

The same test was performed on the b_{1_t}, b_{2_t},...b_{5_t}.

It is expected that F tests for the homogeneity of the b_{0_t} and at least for the linear (N and P) terms will usually be significant (Cady, 1974). Thus the following step is the identification of those measured site variables or "uncontrolled factors" associated with the significant F-values. To accomplish this a three step procedure was used: a) Simple linear correlations between the b_{it} and the site variables were calculated as suggested by Voss and Pesek (1965). b) The b_{it} values were also plotted against each suspected site variable to visualize the type of the relationship as suggested by Culot (1974). c) Simple correlations between pairs of site variables were calculated to have a measure of the multicollinearity. Finally, each one of the b_{it} was regressed on the site variables to find out which controlled factors affected the regression coefficients. The

R^2 criterion, the decrease in the error mean square and the percent reduction in the standard deviation of the dependent variable were used to decide on the inclusion or exclusion of each term in the final model.

For the included variables the ordinary least square procedure was employed in the estimation of each parameter.

The stepwise procedure and the maximum R^2 improvement technique developed by Goodnight (1976) and implemented on a computer program in the SAS76[1] version were also used in the selection of the final model.

The author, J. H. Goodnight, considered the R^2 improvement technique to be superior to the stepwise procedure and almost as good as calculating all possible regression within a subset of independent variables. This technique differs from the forward selection or backward elimination procedures described by Draper and Smith (1966), in the fact that it does not settle on a single model. Instead, it looks for the "best" one variable model, the "best" two variable model and so forth. It first finds the one-variable model producing the highest R^2 statistic. Then another variable, the one which would yield the greatest increase in R^2 is added. Once this two-variable model is obtained each of the variables

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[1]SAS76, means: Statistical Analysis System, 1976 version.

in the model is compared to each variable not in the model. For each comparison, the procedure determines if removing the variable in the model and replacing it with the presently excluded variable would increase the R^2 ratio. After all the possible comparisons have been made, the switch which produces the largest increase in R^2 is made. Comparisons are made again, and the process continues until the procedure finds that no switch could increase R^2. The two-variable model thus settled on, is considered the "best" two variable model the technique can find. The procedure then incorporates a third variable to the model, according to the criteria used in adding the second variable. The comparing and switching process is repeated, the "best" three-variable model is discovered, and so forth.

This technique differs from the stepwise technique in that here all the switches are evaluated before any switch is made. In the stepwise procedure, removal of the "worst" variable may be accomplished without consideration of what adding the "best" remaining variable would accomplish.

Economic Analysis

The rates at which fertilizer should be applied to the wheat crop can be calculated after the response function has been established. However, depending on the criteria chosen to do this, economic or uneconomic recommendations may result. Different procedures to establish the economic optimum rate have been developed and the theory which substantiates those procedures constitutes a whole field of study commonly regarded as Agricultural Production Economics. Thus, it is not intended here to review the basis of those procedures, nor to describe them all. Nevertheless, it is considered appropriate to define some of the terms commonly used, at least those which are going to be employed in the analysis of the data.

Given a functional relationship $Y = f(F)$, where Y is the expected crop yield as a function of the rate of applied fertilizer (F), the relationship between profit and money invested in fertilizer can be derived by:

$$M = V \cdot Y - I - Q$$

where

M = profit,

V = value of a unit of yield,

Y = units of crop yield,

I = investment in fertilizer, and

Q = fixed costs (i.e., the cost of producing the crop excluding the cost of fertilizer).

I is calculated by: $I = C \cdot F$ where C = the cost of a unit of fertilizer and F is the amount being applied.

The yield response to fertilization can then be written as follows:

$$\Delta Y = Y - Y_o,$$

where

Y_o = yield obtained without fertilization.

Thus the corresponding function of profit from the use of fertilization is

$$\Delta M = V \cdot \Delta Y - I.$$

And the rate of return on some differential investment is simply the slope dM/dI, which is the same as dΔM/dI.

In the most common situation when the functions Y, ΔY, M or ΔM are of diminishing form, fixed costs associated with the use of fertilizers are negligible and crop production with nil fertilization still gives a profit. The rate of return dM/dI or dΔM/dI decreases with increase in I, and fertilizer requirement is defined in terms of a minimal marginal rate of return, "R", (Colwell, 1974).

Because of the diminishing form of the response curve, the fertilizer requirement can be defined as that amount of fertilizer which satisfies the equation,

$$dM/dI = R \quad \text{or} \quad d\Delta M/dI = R.$$

Where R is determined from a consideration of the alternative investment available to the farmer. For maximum profit, R = 0. But, since in practice farmers always have some alternative investment to produce a return, fertilizer should not, under usual circumstances, be applied for maximum profit (Colwell, 1974). Then for an optimal investment the marginal rate of return will usually be greater than zero, i.e., $R>0$. Since profit and investment are functions of the amount of fertilizer being applied: $M = V \cdot Y - I - Q$ and $I = C \cdot F$, then $\frac{dM}{dI} = \frac{V}{C} \cdot \frac{dY}{dF} - I$ hence, the adequate fertilization rate can be calculated solving the equation $dY/dF = \frac{C}{V}(R+I)$ or $d\Delta Y/dF = \frac{C}{V}(R+I)$. Since actual alternative investment values are not available for this study, the maximum profit situation will be considered in the calculation of all economic rates of fertilization. If the second degree polynomial is selected to express the factor yield relationship, and the natural and square root scales are used to fit the data, the optimal application rate of N and P are then given by: (for the square root model)

$$Y = b_0 + b_1 N^{0.5} + b_2 N + b_3 P^{0.5} + b_4 P + b_5 (NP)^{0.5}, \qquad (3)$$

$$\frac{dY}{dN} = \frac{b_1 + b_5 P^{0.5}}{2N^{0.5}} + b_2 = \frac{Cn}{V},$$

$$\frac{dY}{dP} = \frac{b_3 + b_5N^{0.5}}{2P^{0.5}} + b_4 = \frac{Cp}{V};$$

and for the quadratic model:

$$Y = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5NP, \qquad (4)$$

$$\frac{dY}{dN} = b_1 + 2b_2N + b_5 P = \frac{Cn}{V},$$

$$\frac{dY}{dP} = b_3 + 2b_4P + b_5N = \frac{Cp}{V},$$

where

V = value of a unit of yield,

Cn = cost of a unit of nitrogen, and

Cp = cost of a unit of phosphorus.

The use of soil testing values in the assessment of the economic rate of fertilization

Since there is an obvious need to vary fertilizer rate between individual farmer's fields within the area, according to their particular fertility level, the use of the soil test values becomes essential. An example of how it will be used is presented here, following the idea of Cady (1974).

The economic optimum combination for Equations 3 and 4 is obtained by equating the derivative of Y with respect to N and P to the price-cost ratio of the fertilizer and the wheat grain. Use of the averaged regression coefficients b_0, b_1,...b_5 across sites has been postulated as a regional recommendation (Colwell, 1974). Nevertheless the level of the soil nutrients (N and P) for an individual field is not taken into account in this way. This situation changes if the level of the site variable (available N and P in the soil) interacts with the controlled or applied variables, namely the N and P rates of fertilization.

Then the model becomes:

$$\hat{Y} = b_0 + b_1N + b_2N^2 + b_3P + b_4P^2 + b_5NP + b_6n + b_7p$$

$$+ b_8nN + b_9pP, \qquad (5)$$

and the economic optimum rates for N and P are given by:

$$\frac{dY}{dN} = (b_1+b_8n) + 2b_2N + b_5P = \frac{Cn}{V},$$

$$\frac{dY}{dP} = (b_3+b_9p) + 2b_4P + b_5N = \frac{Cp}{V}.$$

Now the economic optimum rate does depend on the level of available N and P in the soil.

Identical procedures can be established with any other site variable which has been associated with the response to fertilization throughout the area.

CHAPTER IV. RESULTS AND DISCUSSION

Of the 15 experiments implemented in 1972 only 13 were analyzed. Two were discarded due to an excessive number of missing plots.

The response to N and P fertilization at each site was then analyzed by regressing the average plot yields on the applied fertilizer rates. Two different functional forms were used to express the factor-yield relationship, the second degree polynomial in its natural scale (quadratic model), and the square root function as described in Chapter III.

Each experimental site was identified by a four digit number, the first digit represents the year in which the experiment was performed (2 = 72, 3 = 73, 4 = 74), the second, third, and fourth digits identify the experimental site within each year.

The regression coefficients and the probability values for the Student 't' test (H_o: B = 0) that is, Probability > $|t|$, are presented in Tables 1 and 2. The multiple squared correlation coefficient (R^2) attained by each functional form, at each site, is presented in Table 3. This table indicates that both functional forms attained the same R^2 value in 9 cases, but the quadratic model produced a higher R^2 in 54% of the remaining sites. Considering this, the attained error mean square and the percent reduction

Table 1. Regression coefficients and statistical significance (Prob > |t|) values for the square root model fitted to the average yield response to N and P treatments at 70 sites

Site #	b_0	$b_3\sqrt{P}$	b_4P	$b_1\sqrt{N}$	b_2N	$b_5\sqrt{NP}$
2010	2125	63.09***	-1.3459	53.52***	-3.3069	0.31644
2020	1785	138.53**	-8.1740*	6.93	-0.3775	0.98296
2030	3400	89.74*	-6.0740	35.73	-1.9083	-1.58744
2040	2316	34.93	-4.4884	31.00	-3.5223	2.36741
2050	2431	83.06*	-1.9037	49.26	-5.5527***	1.59974
2060	2473	101.86***	-0.5177	36.36	-0.7385	-4.47036
2070	1665	52.10	0.4160	-47.81	11.5339*	3.69455
2080	2765	22.44	-0.9234	10.43	3.7634	-3.19935
2100	2318	28.21	-1.0157	17.91	-2.4888	1.82551
2120	1878	2.33	0.9132	-54.03	20.4592	-3.03807
2130	1873	-4.83	1.8903	21.34	10.6540**	0.32255
2140	1991	-9.52	3.2159	28.07	-2.5261	3.32788*
2150	2064	53.17***	0.5872	-4.75	2.4735	5.55496*
3012	1489	7.24	0.2761	-57.61*	2.9585	0.25992
3042	1776	66.63*	-6.2667***	-26.56	-0.0664	3.87975

*Significant at 0.05.

**Significant at 0.01.

***Significant at 0.10.

Table 1 (Continued

Site #	b_0	$b_3\sqrt{P}$	b_4P	$b_1\sqrt{N}$	b_2N	$b_5\sqrt{NP}$
3061	1534	-8.73	2.5746	80.08	-13.3786***	0.92827
3102	1128	-33.95*	3.4090*	-13.08	1.2818	3.20555*
3202	2380	101.27*	-9.4832*	-6.62	1.1319	-0.02019
3222	1678	4.19	5.3184	-44.06	3.2886	-2.49424
3302	1719	-8.25	1.8274	21.41	0.4400	2.93402
3011	1356	27.38	-2.9343	-28.66	-1.5534	0.47858
3020	1572	25.70	2.5574	-67.46	5.0753	1.45907
3041	2106	120.05**	-6.9760*	14.58	-3.1327	-4.23564*
3050	1292	33.23	1.3609	-2.65	0.0066	-0.68063
3062	1784	-12.43	2.6312	-33.76	0.8117	4.66888**
3071	1314	-1.03	1.5139	0.03	8.0266*	-2.13647
3080	2353	-13.99	1.9650	44.54	-4.1807	1.82459
3091	2497	30.89	-0.6762	3.96	1.5326	-5.47171
3101	1104	17.92	-1.3769	18.55	-1.3441	0.05145
3110	2246	1.09	-0.6586	59.98	-11.6554*	1.63898
3120	1980	19.55	-2.0239	-13.37	4.4685*	5.57867**
3131	1643	27.39	0.2637	35.29	-3.2548	-1.99705
3140	1312	-15.72	1.9702	36.68	0.2325	1.76320
3180	1819	-4.73	3.7136*	23.50	-1.6334	0.01032
3190	1282	18.73	-1.4520	-2.73	1.6098	1.98974
3201	2352	77.25	-5.5679	-18.40	3.7901	-2.11719
3210	1094	62.45***	-2.1880	75.23*	-4.5537	-1.02246
3221	1370	59.72***	-1.5922	-0.07	-0.2464	0.64519

Table 1 (Continued)

Site #	b_0	$b_3\sqrt{P}$	B_4 P	$b_1\sqrt{N}$	b_2N	$b_5\sqrt{NP}$
3230	2031	42.72	-2.6759	72.08***	-6.1986***	-1.10960
3240	1687	-71.46***	3.8970	-15.73	9.3153	0.43965
3260	2195	-29.62	3.6144	7.87	-3.2443	5.43586**
3270	1685	62.60***	-3.1573	23.83	3.1437	-1.40307
3280	1983	2.32	-1.5798	11.46	-0.8500	2.97769
3290	1800	1.55	1.2668	-29.30	1.6414	2.49133***
3301	1592	1.80	2.5228	80.79**	-4.2982***	-0.56371
3320	2103	77.91**	-4.7956*	33.79***	-3.6621***	0.79828
3330	1838	-37.31	4.6531	58.25	-1.5018	-0.17598
3360	1777	90.79	-7.3140	49.33	-0.5984	-0.86526
3370	1550	61.89	-4.6528	4.20	-0.8750	-0.82867
3380	2645	55.49	-1.1406	82.59***	-11.6195*	0.30924
3390	2348	35.86	-0.4432	21.69	-4.2152	0.46838
3400	2107	-34.56	3.2414	49.66	-5.9288	0.09664
3410	2150	34.33	0.1838	23.69	0.3494	3.25943
3420	2065	95.53**	-3.0185	51.99***	-6.8439*	3.68624***
3430	1194	51.00*	-2.7783	58.58*	-6.0981	-2.76840***
4021	2352	-3.67	2.1516	37.39	-7.4104	10.30086*
4031	1761	-22.20	1.9048	6.94	2.2245	1.78303
4041	2488	-57.06	12.1107**	43.67	-1.9522	1.37203
4051	1110	17.56	-0.6429	-19.58	2.0485	0.35699
4071	1167	21.43	-1.7025	35.72	-1.4945	-1.17612
4081	2242	22.04	2.1913	19.98	-3.0570	4.52746

Table 1 (Continued)

Site #	b_0	$b_3\sqrt{P}$	b_4P	$b_1\sqrt{N}$	b_2N	$b_5\sqrt{NP}$
4091	1997	-21.55	4.7532	-1.96	1.7085	1.81631
4101	1719	26.77	-0.4438	-5.22	6.6618	-1.27536
4111	1628	9.07	2.2085	-8.54	4.5157	3.75518***
4131	2370	91.16*	-5.9229	-1.36	-1.1169	3.48317
4141	2882	0.81	-1.9834	21.04	-0.7486	3.93029
4161	2319	91.83***	-3.7314	6.94	-1.0941	2.01876
4171	1759	37.75	2.2134	31.13	-1.9700	-2.55108
4191	2447	104.09*	-9.3618*	85.63***	-9.0005*	2.33520
4211	1666	162.15*	-9.3089	35.15	-3.5667	-4.48958

Table 2. Regression coefficients and statistical significance values for the quadratic model fitted to the average yield response to N and P treatments at 70 sites

Site #	b_0	b_3P	b_4P^2	b_1N	b_2N^2	b_5NP
2010	2095	12.23**	-0.06949**	8.38**	-0.0599*	-0.007641
2020	1819	17.59**	-0.12623**	1.44	-0.01319	0.014658
2030	3435	9.80*	-0.07357***	3.78	-0.02375	-0.015435
2040	2283	6.80	-0.07849***	2.86	-0.03296	0.024841
2050	2448	16.12**	-0.10177**	3.46	-0.04413***	0.020635
2060	2516	18.63**	-0.09574*	1.35	0.01208	-0.045529

*Significant at 0.05.

**Significant at 0.01.

***Significant at 0.10.

Table 2 (Continued)

Site #	b_0	b_3P	b_4P^2	b_1N	b_2N^2	b_5NP
2070	1576	13.82**	-0.07663*	7.20***	0.00547	0.026800
2080	2747	2.05	-0.00438	5.56***	-0.00401	-0.043388***
2100	2316	5.40*	-0.03618***	1.88	-0.02563	0.018611
2120	1895	-0.50	0.01277	8.02*	0.06927*	-0.026658
2130	1879	0.66	0.00554	15.61**	-0.031320***	0.007859
2140	1971	4.23***	-0.01729	4.22***	-0.038690***	0.033247*
2150	2081	12.62**	-0.06976*	3.35	-0.014060	0.063270*
3012	1485	1.54	-0.0043	-13.18**	0.1794**	-0.00140
3042	1768	8.77**	-0.0961**	-3.00	-0.0394	0.09013*
3061	1557	0.97	-0.0009	9.97	-0.29638*	0.05228
3102	1089	-1.05	0.01486	0.96	-0.01944	0.04297
3202	2386	10.39*	-0.10680*	1.13	-0.02611	0.00448
3222	1751	2.03	0.02618	-12.57	0.15027	0.01477
3302	1725	0.20	0.0084	8.11	-0.1025	0.05464
3330	1874	-2.52	0.02965	8.02***	-0.04715	0.012980
3360	1794	10.74**	-0.09797**	8.65**	-0.04722**	-0.009911
3370	1544	7.20*	-0.05458***	-0.27	0.00472	-0.024111
3380	2597	12.33*	-0.07055	5.26	-0.077638	-0.027860
3390	2341	7.12***	-0.04229	1.03	-0.03270	0.004166
3400	2123	-4.04	0.04215	2.84	-0.040347	0.000166
3410	2146	9.05**	-0.05923***	5.95***	-0.03506	0.04163***
3420	2067	17.60**	-0.11896**	5.17	-0.07285*	0.044740
3430	1211	6.34**	-0.04187*	4.04*	-0.0445*	-0.038630*

Table 2 (Continued)

Site #	b_0	b_3P	b_4P^2	b_1N	b_2N^2	b_5NP
4021	2244	11.23***	-0.09340	4.98	-0.08354	0.109900*
4031	1738	-1.76	0.02326	4.35	-0.00798	0.007520
4041	2433	1.99	0.05868	9.19*	-0.062986***	-0.004611
4051	1081	5.97	-0.05388	-1.80	0.02000	0.005480
4071	1199	0.98	-0.007916	4.36***	-0.02694	-0.010150
4081	2204	8.62***	-0.04333	5.11	-0.0650	0.052488
4091	1984	3.65	-0.01493	0.94	0.00368	0.028811
4101	1761	1.21	0.008194	5.38	0.00444	-0.008730
4111	1622	4.79	-0.019027	5.13***	-0.01722	0.049840*
4131	2333	15.06**	-0.12437**	1.35	-0.023958	0.034922
4141	2829	0.35	-0.01520	6.98	-0.052152	0.031144
4161	2305	18.59**	-0.14770	0.84	-0.017847	0.034500
4171	1759	9.95**	-0.04305*	3.18	-0.021805	-0.032950*
4191	2429	14.93**	-0.15097**	9.56**	-0.10833**	0.029220
4211	1671	24.32**	-0.19062**	1.21	-0.01465	-0.054940

Table 3. Multiple squared correlation coefficient (R^2), for the square root and quadratic model at each experimental site

Site #	2010	2020	2030	2040	2050	2060	2070	2080	2100	2120	2130	2140	2150	3011
R^2, for square root model	0.88	0.89	0.57	0.31	0.93	0.79	0.94	0.65	0.81	0.97	0.99	0.92	0.96	0.73
R^2, for quadratic model	0.92	0.86	0.53	0.47	0.95	0.84	0.95	0.72	0.79	0.97	0.99	0.90	0.95	0.76

Site #	3012	3020	3041	3042	3050	3061	3062	3071	3080	3091	3101	3102	3110	3120
R^2, for square root model	0.85	0.79	0.90	0.65	0.84	0.49	0.87	0.86	0.56	0.24	0.17	0.73	0.56	0.96
R^2, for quadratic model	0.86	0.78	0.84	0.77	0.83	0.58	0.88	0.87	0.54	0.18	0.14	0.64	0.48	0.95

Site #	3131	3140	3180	3190	3201	3202	3210	3221	3222	3230	3240	3260	3270	3280
R^2, for square root model	0.62	0.81	0.88	0.75	0.26	0.40	0.81	0.82	0.50	0.45	0.76	0.84	0.78	0.25
R^2, for quadratic model	0.55	0.84	0.88	0.76	0.20	0.38	0.79	0.83	0.50	0.46	0.79	0.81	0.78	0.29

Site #	3290	3301	3302	3320	3330	3360	3370	3380	3390	3400	3410	3420	3430	4021
R^2, for square root model	0.81	0.85	0.60	0.91	0.69	0.93	0.51	0.71	0.67	0.30	0.90	0.94	0.71	0.76
R^2, for quadratic model	0.77	0.85	0.61	0.95	0.64	0.94	0.50	0.71	0.69	0.25	0.90	0.92	0.77	0.76

Site #	4031	4041	4051	4071	4081	4091	4101	4111	4131	4141	4161	4171	4191	4211
R^2, for square root model	0.70	0.87	0.18	0.51	0.78	0.69	0.74	0.91	0.82	0.62	0.78	0.85	0.72	0.62
R^2, for quadratic model	0.68	0.88	0.31	0.45	0.79	0.70	0.73	0.92	0.83	0.58	0.88	0.90	0.84	0.76

in the standard derivation of the dependent variable, the quadratic model was selected to represent the data across sites.

In 73% of the cases both models explained more than 65% of the variation in yield response due to fertilization. The absolute difference between observed and predicted values $|Y-\hat{Y}|$, was almost always less than 150 kg/ha, it exceeded 300 kg/ha only in 8 cases out of the 1094 observations.

Figures 6 to 12 show the predicted and the observed yield values for seven different sites. Since it was not feasible to include the graphical yield response for each model at each site, 10% of them were selected to illustrate the different types of yield responses to fertilization across years and sites.

By the analysis and plotting of the residual values $(Y-\hat{Y})$, it was concluded that both functional forms fitted the data adequately. However, since values for the individual replications were not available a test for the lack of fit was not possible.

Since in the first year of experimentation (1972) the treatment design was different from the rest and in 1973 seven trials received only the first N application, the seventy trials were divided into three groups 13, 7 and

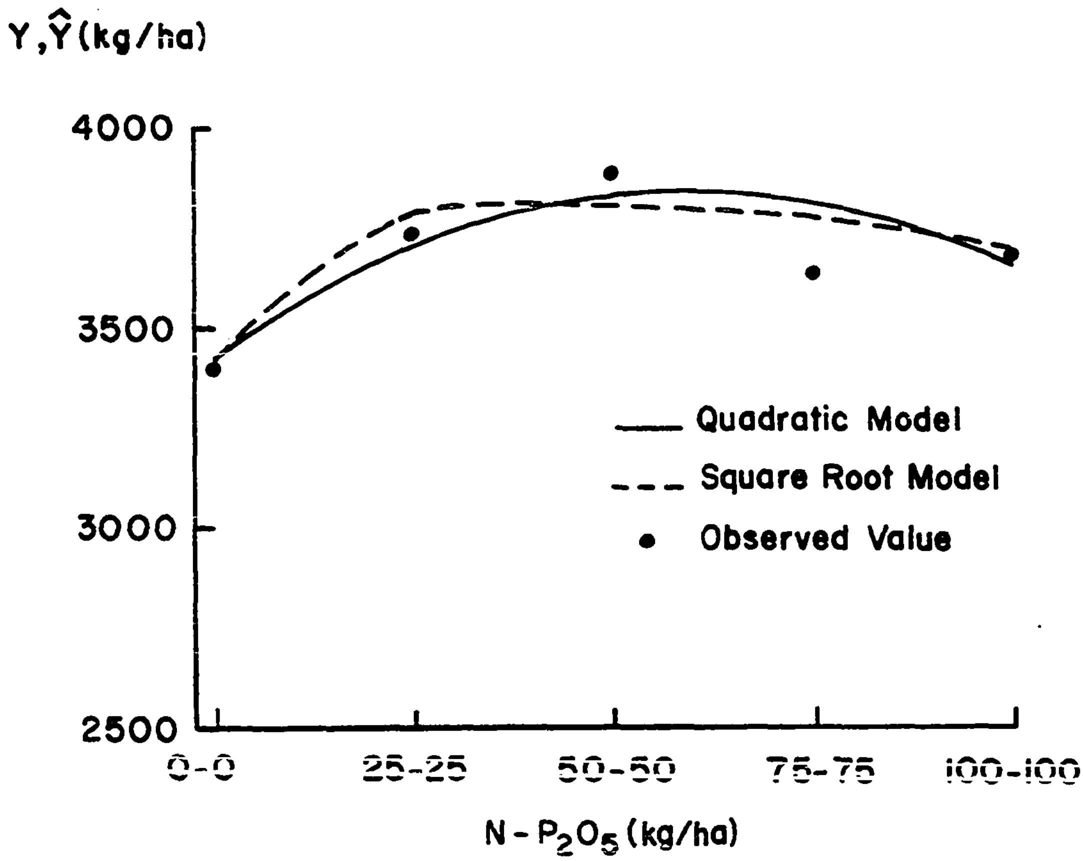

Figure 6. Observed and predicted yield values for site #2030

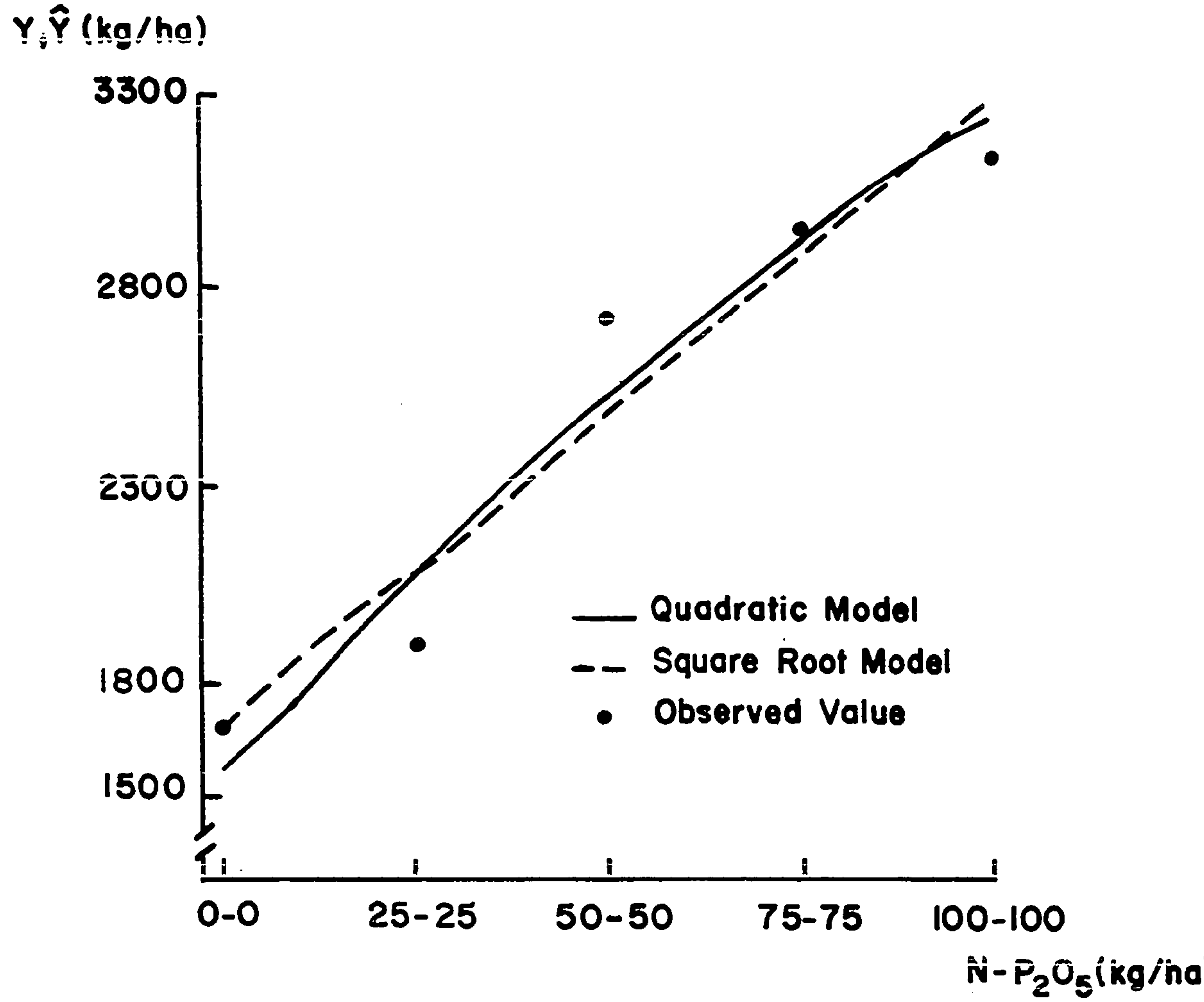

Figure 7. Observed and predicted yield values for site #2070

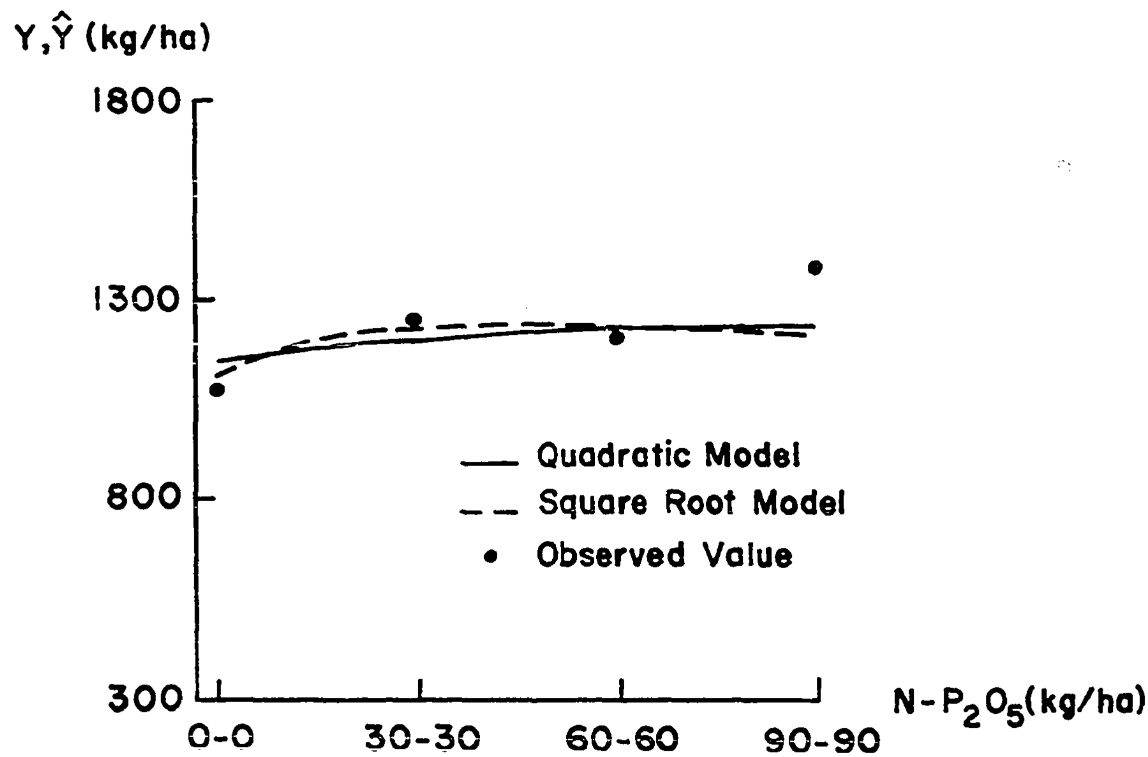

Figure 8. Observed and predicted yield values for site #3101

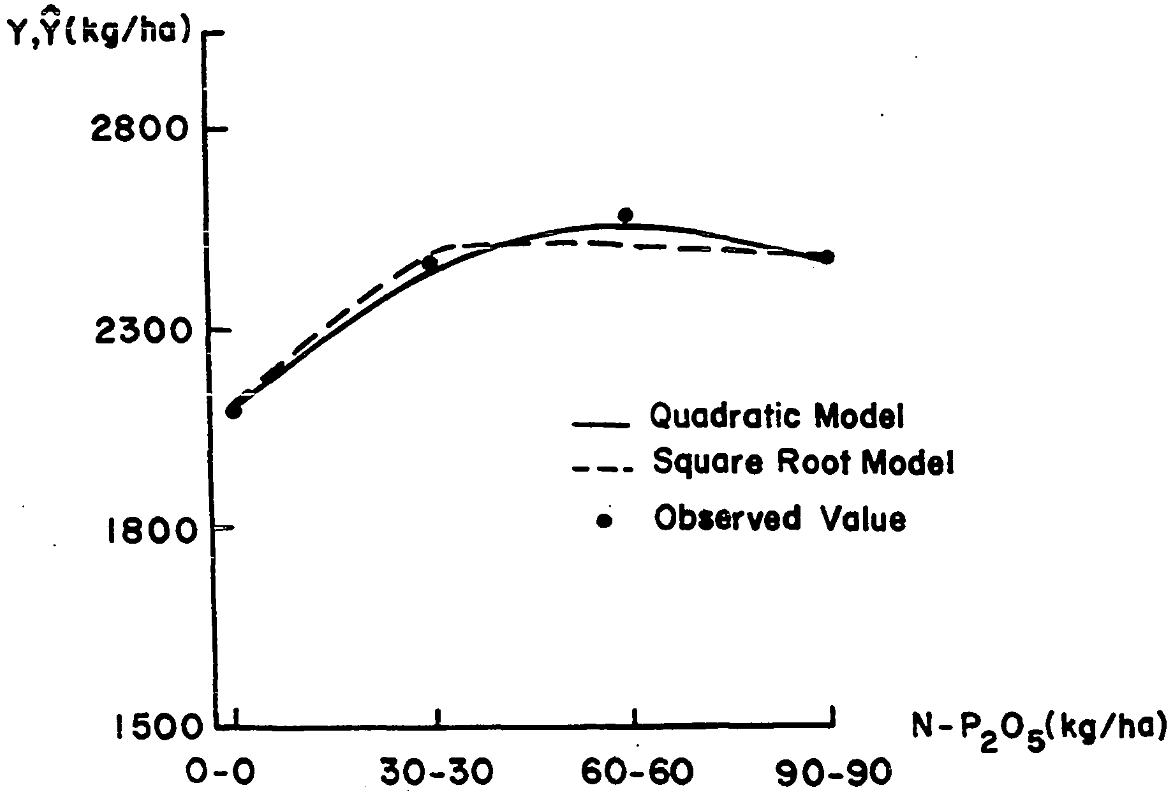

Figure 9. Observed and predicted yield values for site #3270

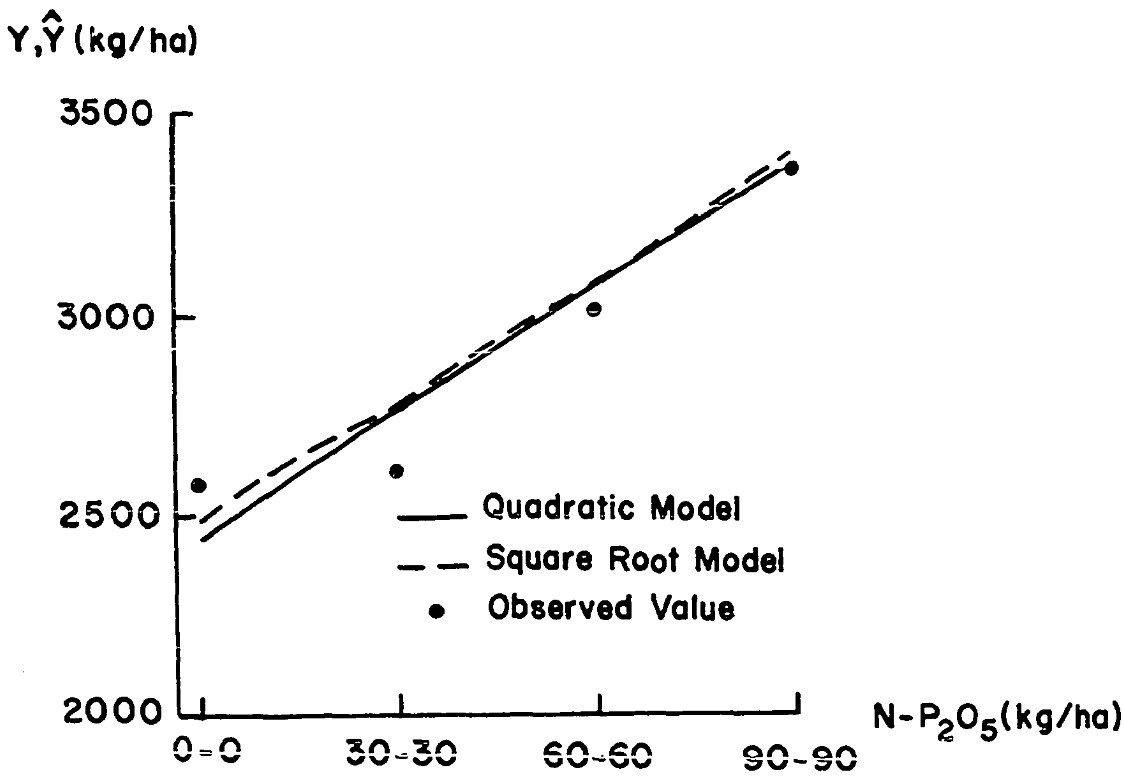

Figure 10. Observed and predicted yield values for site #3320

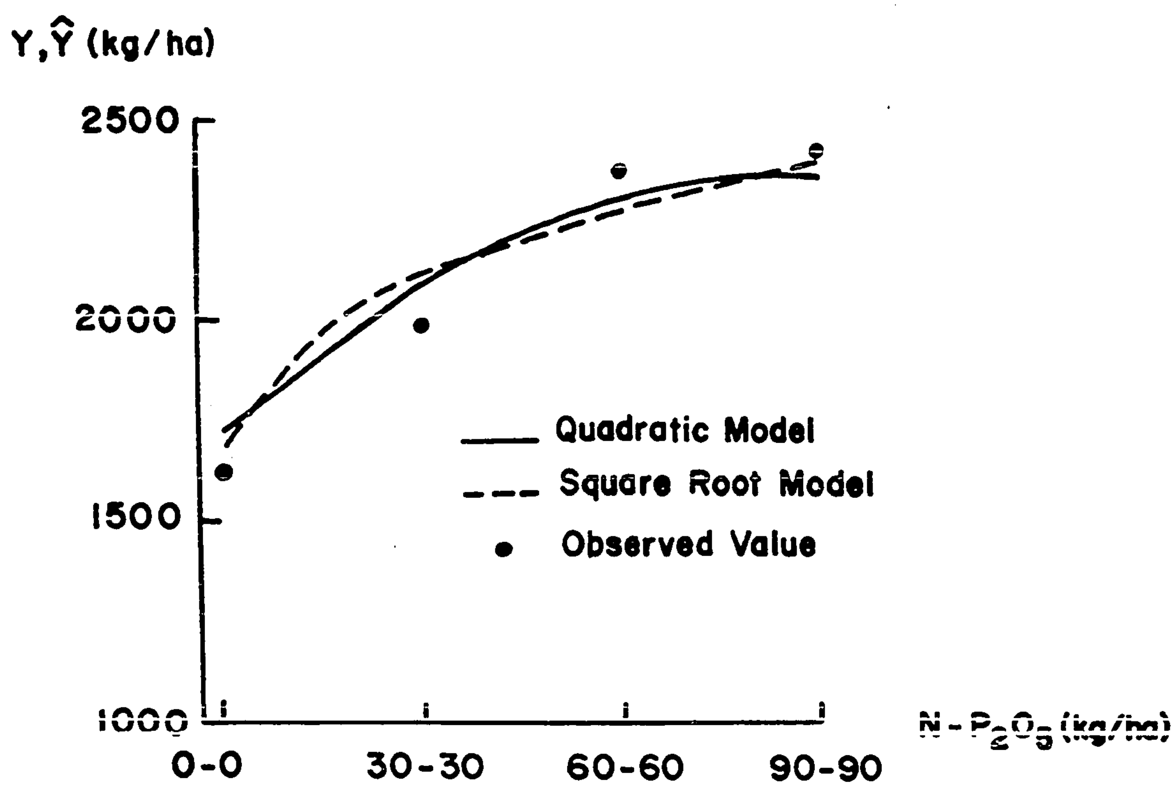

Figure 11. Observed and predicted yield values for site #4041

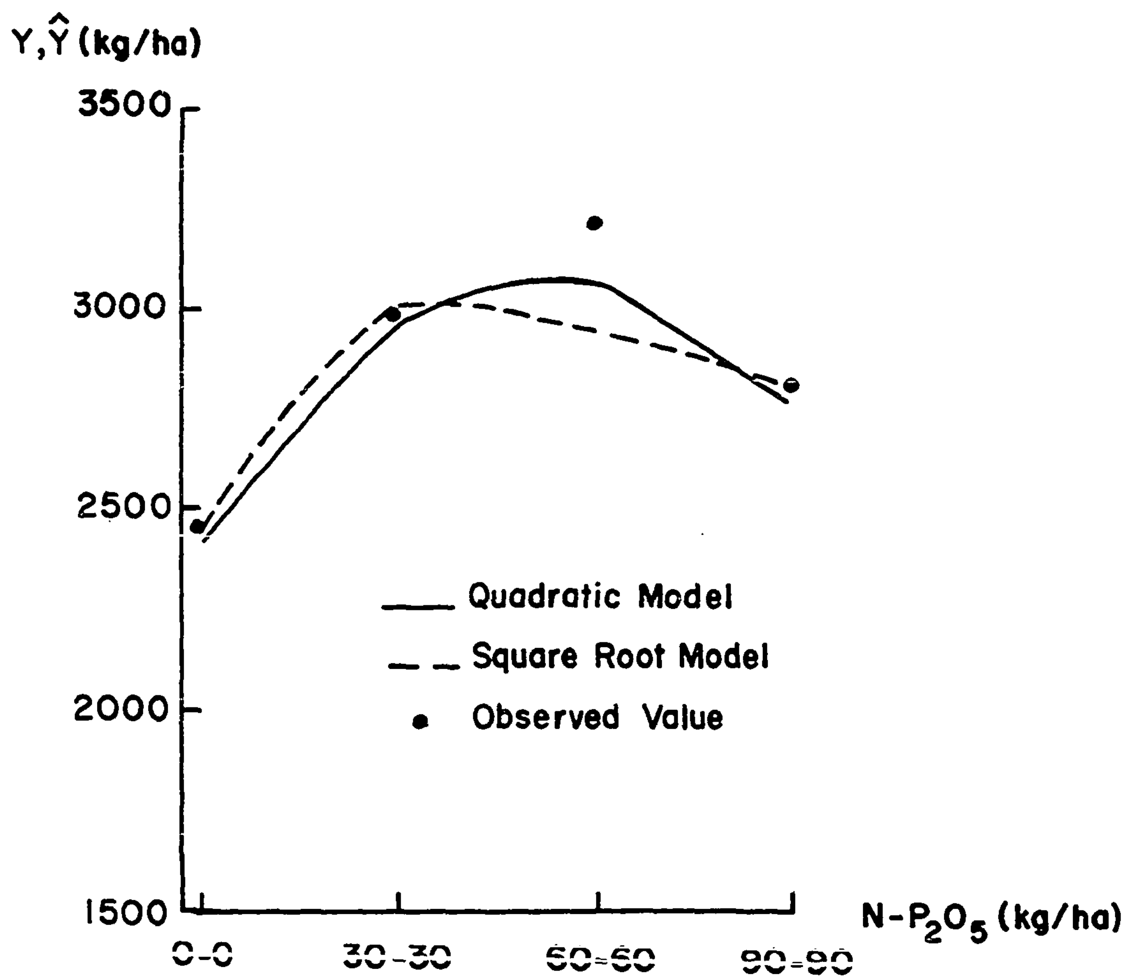

Figure 12. Observed and predicted yield values for site #4191

50 experiments respectively, in order to perform the F-test across sites for the b_0, b_1, b_2, b_3, b_4 and b_5 regression coefficients.

The test for the b_0 coefficients resulted in a significant difference at $P = 0.01$ for the three groups analyzed. The b_1(N) coefficients were significantly different at $P =$ 0.25 in the first group (1972 trials), and in the second group (7 trials from 1973). They differed significantly at $P = 0.05$ in the third group (50 trials, 35 from 1973 and 15 from 1974).

The b_2 (N^2) coefficients were not significantly different at $P = 0.25$, in any of the three groups tested. The b_3 (P) coefficients were significantly different at $P = 0.001$ in the first and third group, and showed a significant difference at $P = 0.25$ for the second group (seven experiments in 1973). The b_4 (P^2) coefficients were significantly different at $P = 0.01$, 0.07 and 0.001 in the first, second and third group, respectively.

The b_5 (NP) coefficients were significantly different at $P = 0.05$ in the first group and at $P = 0.10$ in the third group, but they did not show any difference in the second group ($F<1$).

By examining the yield increments obtained with N and P fertilization at each site (Table 10), it can be concluded that eleven trials showed no response to fertilization, nineteen responded to P alone, thirteen responded to N alone, and twenty-seven responded to N+P. However, the significance value for the regression coefficients for the quadratic model at each site (Table 2) showed that 33 sites produced a significant positive linear effect of P application and 23 sites showed a significant positive linear effect of N application. In four cases the linear response to N was significant and negative. The interaction NP was significant and positive at 10 sites and significant but negative in 4 cases. The quadratic term for P was significant and negative in 25 cases, the quadratic term for N was significant and negative in 17 cases and significant but positive in 2 cases.

In order to identify both applied and site variables and the interaction terms among them, an abbreviation code was selected as it is shown in Table 4. The abbreviations or the full name for each variable are used in this and the following chapters.

The simple linear correlation between pairs of uncontrolled factors showed a high degree of association between organic matter and total nitrogen in the A horizon as was expected, r = 0.82. Another highly correlated pair was the cation exchange capacity and the clay content of the A

Table 4. Full names and abbreviations for the controlled, uncontrolled variables, and interaction terms used

Abbreviation	Variable description (full name)
N	Applied nitrogen in kg/ha
N^2	Applied nitrogen, quadratic effect, in kg/ha
P	Applied phosphorus in kg of P_2O_5 per ha
P^2	Applied phosphorus, quadratic effect, in kg of P_2O_5 per ha
NP	NxP interaction of applied nutrients
Y	Wheat grain yield in kg/ha
$Y_{(ch)}$	Yield obtained without fertilization, i.e., check plot yield
$\hat{Y}$	Estimated or predicted yield in kg/ha
ni	Potential nitrification index for the A horizon, in ppm
ni_1	Nitrates present in the soil at seeding time from 0 to 20 cm, in ppm
ni_2	Nitrates present in the soil at seeding time from 20 to 50 cm, in ppm
ni_3	Weighted average for nitrates present in the soil at seeding time from 0 to 50 cm, in ppm
nt_1	Nitrates present in the soil at tillering time from 0 to 20 cm, in ppm
nt_2	Nitrates present in the soil at tillering time from 20 to 50 cm, in ppm
nt_3	Weighted average for nitrates present in the soil at tillering time from 0 to 50 cm, in ppm
tn	Percent total nitrogen in the A horizon
om	Percent organic matter in the A horizom
p	Available phosphorus in the A horizon, in ppm
pH	Soil pH for the A horizon

Table 4 (Continued)

Abbreviation	Variable description (full name)
ca	Percent clay in the A horizon
cb	Percent clay in the B horizon
cc	Cation exchange capacity for the A horizon, in mq/100 gr of soil
st	Soil aggregates stability index
so	Solum thickness, in cm
ta	Thickness of the A horizon, in cm
tb	Thickness of the B horizon, in cm
npl	Nitrates in plant tissue at tillering time, in ppm
tnp	Percent total nitrogen in plant tissues at tillering time
d	Number of stress days from heading to dough stage
R_1	Rainfall in mm, from sowing to tillering
R_2	Rainfall in mm, from tillering to booting
R_3	Rainfall in mm, from booting to milky stage
R_4	Rainfall in mm, from milky stage to maturity
R_{12}	$R_1 + R_2$
R_{23}	$R_2 + R_3$
R_{34}	$R_3 + R_4$
TR	$R_1 + R_2 + R_3 + R_4$, total rainfall from sowing to maturity
L	Number of years since last legume crop
re	Number of years since last natural, temporary or permanent pasture[a]
w	Weed infestation, scale of 0 to 5 was used[a]

[a]For more details, see references in the Appendix.

Table 4 (Continued)

Abbreviation	Variable description (full name)
f	Fallow length in weeks
np	ni_1 x p
omf	om x f
dp	d x p
pf	p x f
Rni	R_1 x ni_1
wd	w x d
sd	so x d
Nd	N x d
db	d x tb
Nni_1	N x ni_1
Pp	P x p
Pd	P x d
Nom	N x om
Pni	P x ni_1
Ncb	N x cb

horizon, r=0.64.** Among the different nitrogen availability indexes considered, several significant correlations were detected. The amount of nitrates present in the soil at seeding time from 0 to 20 cm was highly correlated with the weighted average of nitrates present in the soil from 0-50 cm.

The amount of nitrates present at seeding time from 20 to 50 cm was highly correlated with the amount present at tillering time at the same depth, r = 0.69.**

The potential nitrification index was significantly associated with the amount of total nitrogen in plant tissue at tillering time, r = 0.56**. The amount of nitrates in plant tissue at tillering time was also highly correlated with the amount of total N in plant tissue, r = 0.66**. The matrix correlation showing this and every other possible correlation between pairs of uncontrolled factors is given in Table 5 (Appendix).

The correlation between the linear regression coefficients, b_1N and b_3P (quadratic model), and each site variable revealed a significant negative association between b_1N and the number of moisture stress days, r = -0.49**, and also a significant negative association between b_1N and the amount of nitrates present in the soil at seeding time from 0 to 50 cm, r = -0.28*. The b_3P was correlated significantly with the amount of available phosphorus in the soil, r = -0.30*, with the potential nitrification index, r = 0.40**, and with the clay percentage of the B horizon, r = 0.29*. These and other correlations are shown in Table 6 (Appendix).

The correlation between the average yields without fertilization and the uncontrolled site variables showed that the variation in yield was well-correlated with the number of moisture stress days, r = 0.53**, with the cation exchange capacity of the A horizon, the thickness of the B horizon and the potential nitrification index among others (Table 5).

A multiple regression equation showed that nine uncontrolled factors explained 54% of the observed variation in yield without fertilization. The nine variable model which produced the smallest error mean square is:

$$\hat{Y}_{(ch)} = 1003.4 - 26.24\, d + 9.605\, ni - 89.94\, w - 0.222\, Rni - 1.097\, d_{B} + 57.00\, ca + 14.56\, ni_1 - 6.93\, omf + 1.60\, R_2. \qquad (6)$$

The probability level and the standard error for each coefficient are given in the Appendix, Table 14. The addition of three more variables to the model increased the R^2 up to 0.551, but also increased the error mean square 3.7%.

Predicted values for $Y_{(ch)}$, calculated from Equation 6, showed good agreement with the observed $Y_{(ch)}$ values. The absolute average for the residuals, $|Y_{(ch)} - \hat{Y}_{(ch)}|$, was 254 kg/ha which was smaller than the standard deviation for $Y_{(ch)}$ (332 kg/ha).

When the uncontrolled site variables were regressed on the b_1N and b_3P coefficients obtained at each site, it was found that 12 factors explained 59% of the variation in the b_1N coefficients and seven factors explained 55% of the variation in the b_3P coefficients. The resulting models are:

$$\hat{b}_1 = 4.60 + 2.65\ \mathrm{pH} + 2.09\ \mathrm{om} + 0.007\ \mathrm{np} - 0.26\ \mathrm{ca}$$
$$- 0.33\ \mathrm{d} - 0.898\ \mathrm{w} - 0.232\ \mathrm{cb} - 0.088\ \mathrm{so} - 0.202\ \mathrm{tb}$$
$$- 0.152\ \mathrm{ni}_1 + 0.626\ \mathrm{re} + 0.294\ \mathrm{ta}, \text{ and} \tag{7}$$

$$\hat{b}_3 = 33.79 - 4.73\ \mathrm{pH} - 0.54\ \mathrm{p} + 0.27\ \mathrm{cb} - 2.27\ \mathrm{st}$$
$$+ 0.235\ \mathrm{tb} - 0.507\ \mathrm{ta} + 0.131\ \mathrm{ni}. \tag{8}$$

The probability level for each coefficient is given in the Appendix, Tables 15 and 16.

The first intent in the search for the final yield equation included all 70 experiments, 1094 observations collected throughout the area during 1972, 1973 and 1974. Using the maximum R^2 improvement procedure a model with twelve variables was selected. It yielded the lowest error mean square and explained 58% of the variability in yield. All the coefficients were significant at $P = 0.05$, with the exception of two that were forced into the model. The selected equation is:

$$\hat{Y} = 2561 + 4.78\ N + 7.68\ P + 0.0135\ NP - 0.0166\ N^2$$
$$- 0.0331\ P^2 - 0.279\ Pp - 0.177\ Nd - 9.386\ cb$$
$$- 149.05\ w + 8.51\ ca - 0.388\ sd + 6.51\ cc\ . \qquad (9)$$

It is important to mention that all the variables in the model can be measured before seeding time. The intention was to obtain a prediction equation useful in the assessment of the individual fertilizer needs for each field and not the mere fitting of the observations.

The pooling of the 70 experimental sites implied the mixing of soils with different biophysical and chemical properties, which not only respond differently to fertilization but have different yield potentials. Hence, Equation 9 is useful only as a general estimator of the fertilizer requirements for the entire area.

Because the texture of the B horizon, more specifically the clay percentage, is a good indicator of several biophysical and chemical properties of the soil, it was decided to divide the 70 experimental sites into two groups according to the percentage of clay in the B horizon. A threshold of 25% clay was established; hence the two groups resulted in 15 experimental sites which had less clay than the threshold value and 55 sites with values above it. Even though this limit could seem arbitrary, it grouped soils of the same sub-order. The group of soils with less than 25% clay in the

B horizon include all the Hapludolls, one Udic Haplustoll, and three Argiudolls with a light textured B horizon.

In order to assess the fertilizer requirements of each group, two different models were developed. Equation 10 attempts to estimate the yield response to N and P fertilization in soils with less than 25% clay in the B horizon. It includes five linear, two squared, and eight interaction terms:

$$\hat{Y} = 694.65 + 24.52\ N + 6.22\ P - 0.005\ N^2 - 0.0163\ P^2 + 13.82\ ni_1 - 0.013\ Nni_1 - 0.136\ Nd - 29.47\ wd - 1.95\ dp + 49.03\ ta + 12.51\ p - 0.110\ Pp - 0.883\ Ncb - 0.106\ Rni - 0.099\ Pni. \qquad (10)$$

This equation explains 66% of the yield variation. It is also noticeable here that all the included soil variables can be measured before seeding time. The climatic factors, d and R_1, which are components of three interaction terms have to be estimated, but by using probability techniques and past rainfall record this can be accomplished easily. The same is valid for the degree of weed infestation (w). Even though this variable can not be measured before seeding time, predicted yields can be calculated for different degrees of weed infestation.

Equation 11 attempts to estimate the yield response to N and P fertilization for soils with more than 25% clay in the B horizon. It includes six linear, two squared, and seven interaction terms, and explains 60% of the variability in yield among the 866 observations. The prediction equation is given by:

$$\hat{Y} = 2674 + 1.82\ N + 9.44\ P + 0.016\ NP - 0.021\ N^2 - 0.039\ P^2 - 0.294\ Pp - 0.0935\ Nni_1 - 0.077\ Nd - 0.079\ Pd - 16.47\ cb - 114.4\ w + 13.51\ ca + 0.82\ Nom - 0.384\ sd + 3.547\ tb. \qquad (11)$$

Predicted yield values ($\hat{Y}$) were then calculated for Equations 10 and 11 and compared with each observed (Y) value. In the case of the coarse soils, it was found that the model predictions were satisfactory in 14 out of the 15 sites analyzed. The site at which the response to fertilization was underestimated corresponded to a soil pedon different from the rest. In fact it was the only Udic Haplustoll in the seventy locations analyzed. For the remaining 214 observations (14 sites) the absolute difference between observed and predicted values was less than 500 kg in 91% of the cases and exceeded the standard deviation of Y (356 kg/ha) in 24% of the cases. The absolute residual values $|Y-\hat{Y}|$ for the group of soils with more than 25% clay in the B horizon exceeded the standard deviation of Y (358 kg/ha) in 33% of the cases.

Since the inclusion of some variables which were measured during the crop cycle significantly increased the R^2 in most of the postulated models, an attempt to estimate its variability was done. Using the available information from 1973 and 1974 experiments, three models were developed to predict the amount of nitrates present in the soil at tillering time at two different depths, 0-20 and 20-50 cm, and the percent of total nitrogen present in the plant tissue at tillering time.

The selected equations are:

$$\hat{n}t_1 = 23.44 - 0.794\ ca + 0.443\ ni_1 - 0.0747\ R_1, \qquad (12)$$

$$(R^2 = 0.37)$$

$$\hat{n}t_2 = 14.02 + 0.217\ nt_1 + 0.455\ ni_2 - 0.222\ ta - 0.166\ cb - 0.229\ f,\ (R^2=0.65), \qquad (13)$$

and

$$\hat{t}np = 1.986 + 0.024\ ni + 0.0294\ ni_3 - 0.0036\ R_i \qquad (14)$$

$$(R^2 = 0.48)$$

Even though the probability of each coefficient, Prob > $|t|$, was high (0.05) in the three postulated equations, only one of them, Equation 13 attained an R^2 higher than 0.50.

This was in part due to the contribution of nt_1 which by itself explained 11% of the variation. ni_2 was the most highly associated variable with nt_2, and its presence alone in the model explained 47% of the observed variation in nt_2. The pH of the soil showed a significant linear correlation with nt_1 and nt_2, and its inclusion in the model increased the R^2 1%, but the standard error was so large that it was removed from the model by the stepwise procedure. Almost half of the observed variation in percent total nitrogen in plant tissues was explained by three variables, the nitrification potential index, nitrates present in the soil at seeding time from 0 to 50 cm, and the rainfall from seeding to tillering. The probability level for each coefficient is given in the Appendix (Tables 20, 21 and 22).

The amount of nitrates in plant tissue at tillering time was well correlated with the percent total nitrogen in plant tissue, $r = 0.66^{**}$. Nevertheless, the percentage of total nitrogen in the plant was correlated better with the response to N (b_1N) than with the amount of nitrates in plant tissue. An explanation for this fact could be that the plants were sampled at different times during the day. It is well documented in the literature (Hageman et al., 1961) that diurnal variation and other light effects influence the activity of nitrate reductase in plant tissues, and consequently the amount of nitrates present in the tissue varies with the time of the day.

Even though the nitrates present at seeding time from 0 to 50 cm were correlated better with the response to nitrogen fertilizer than any other nitrogen availability index tested, they were not included in the final equations because data for the second depth (20 to 50 cm) was only recorded after the first year of experimentation. Because initial nitrates at seeding time from 0 to 20 cm was the second best correlated variable with the response to N, $r = 0.22^{***}$, and it was measured from the beginning of the experiments in 1972, it was used in all the prediction equations as the nitrogen availability indicator.

The organic matter content of the surface horizon was correlated positively with the response to nitrogen fertilization, $r = 0.23^{*}$. Perhaps its influence on soil aggregation ($r = -0.33^{**}$)[1] or on water retention was more important than its influence on nitrogen supply. The total nitrogen content of the surface horizon was also positively correlated with the response to N fertilization, $r = 0.236^{*}$. No other explanation than its high association with organic matter content was found. The potential nitrification index was significantly correlated with the yield variation of the check plot,

[1]The reason for the negative sign of the coefficient is that the instability index for the degree of aggregation was used.

$r = 0.24^*$. However, it was very poorly associated with the response to N fertilization.

The phosphorus availability in the surface horizon decreased with the increase of organic matter and clay content of the solum. This implies that the coarser textured soils have a greater amount of available P in the surface horizon than the finer textured soils analyzed. This difference in texture was suspected to be one of the possible causes for the low correlation obtained between p and b_3P. Nevertheless, partial correlations between b_3P and p holding the effect of ca, cb, om or pH constant, did not improve the original relationship.

New partial correlations were sought, holding d and ni constant. In the first case very little improvement was obtained, but in the second case, when ni was held constant the correlation among b_3P and p improved from -0.30* to -0.39**. This indicates that soils with different nitrification potential responded different to P fertilization, that is, the higher the nitrification potential the higher was the response to P fertilization.

From Equations 10 and 11 the rates of N and P which produced the maximum yield were calculated, using average values for the uncontrolled soil variables and assuming that no moisture stress occurred ($d = 0$). For the soils with less than 25% clay in the B horizon, the rate combination which produced the maximum yield (4034 kg/ha) was 511 kg of N and 116 kg of P_2O_5 per ha. For the soils with more than 25% clay in the B horizon, when identical conditions are assumed, the rate combination that produced the maximum yield (2968 kg/ha) was 125 kg of N and 118 kg of P_2O_5 per ha.

The reason for the lower maximum yield attained by the group of soils with more than 25% clay in the B horizon can be found in the fact that the average amount of p in the surface horizon was higher in the group of coarser soils and also in the fact that coarser soils have an average thicker solum than the soils with more than 25% clay in the B horizon. This last group of soils frequently presented a solid impermeable layer of $CaCO_3$ that constituted a serious limitation to the water storage capacity of the soil as well as to root development.

The predicted yield response to N and P fertilization for each group of soils was then calculated, assuming different levels of moisture stress and keeping all other variables at their average group level. The results are presented in Figures 13 and 14.

From Equations 10 and 11, economic optimum rates for N and P fertilizers were calculated, holding the values of the uncontrolled soil variables at their average group levels and assuming different degrees of moisture stress. For the group

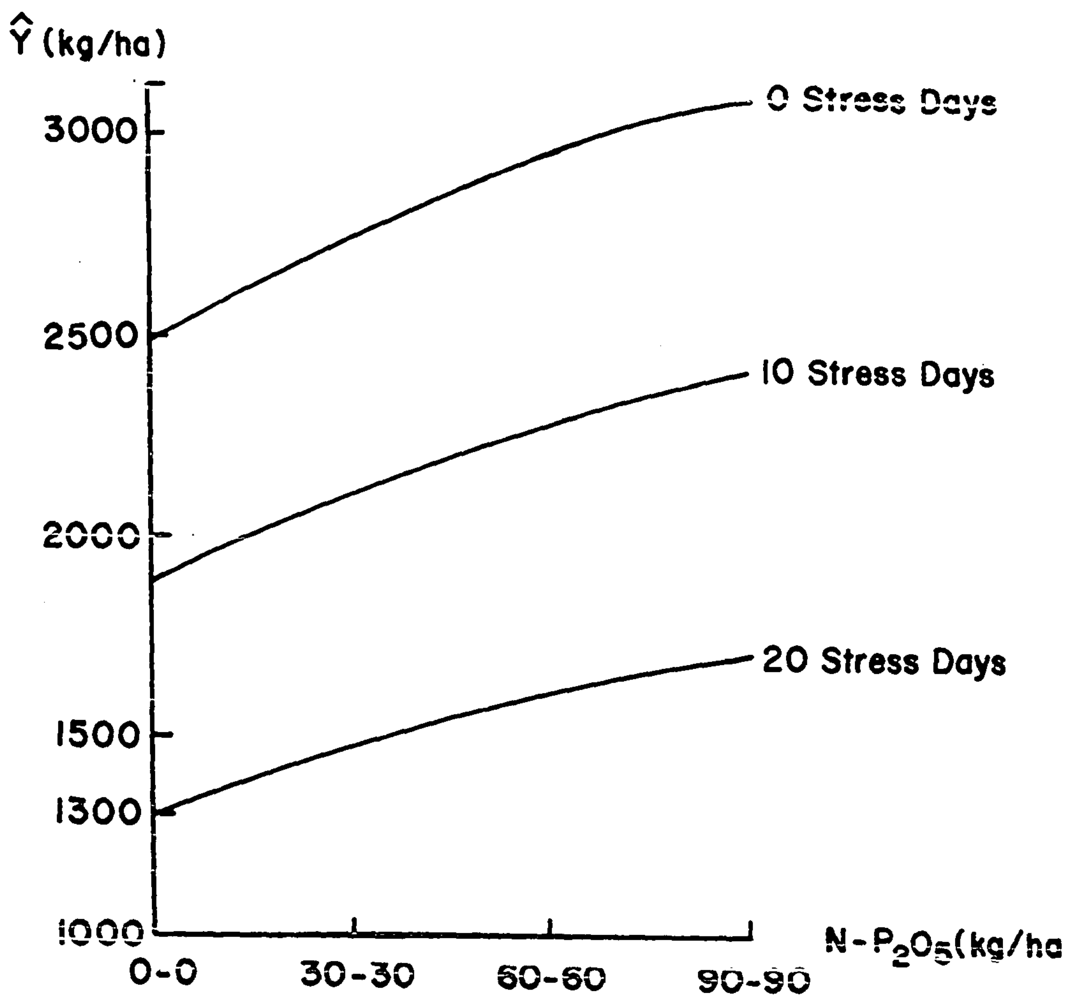

Figure 13. Predicted yield response to N and P fertilization under different moisture stress conditions, for soils with less than 25% clay in the B horizon

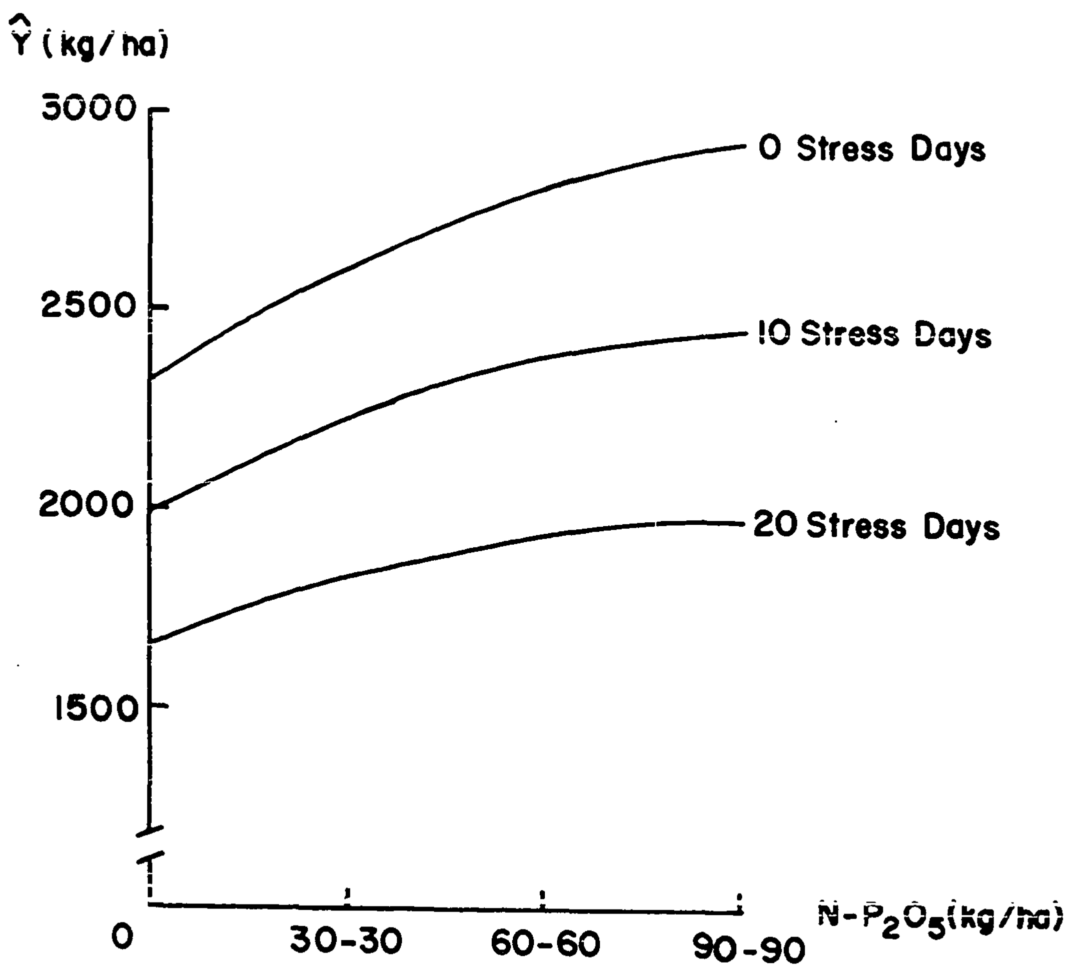

Figure 14. Predicted yield response to N and P fertilization under different moisture stress conditions for soils with more than 25% clay in the B horizon

of soils with less than 25% clay in the B horizon the optimum rate of N applications is independent of the amount of P being applied because the interaction NP was not significant, hence the optimum rate of N is given by Equation 15:

$$\frac{dY}{dN} = 24.52 - 0.013\ ni - 0.136\ d - 0.883\ cb$$

$$- 2(0.005)\ N = \frac{Cn}{V} \qquad (15)$$

where

the average ni value = 14.25 ppm,

the average cb value = 21.77%,

Cn = 0.37 \$/kg,

V = 0.082 \$/kg,

$\frac{Cn}{V}$ = 4.51, and

d is assumed to be 0, 5, 10, 15, 20.

When

d = 0 the optimum N rate = 60.5 kg/ha, and

d = 5 the optimum N rate = 0 kg/ha.

However, if the amount of clay in the B horizon is less than the average value for the group, the situation is completely different, which indicates that the amount of clay in the B horizon is the controlling factor. This is easily noticed by the magnitude of the cb coefficient in Equation 15. For instance, if the amount of clay in the B horizon is 1% lower than the average for the group, the economic optimum rate of N becomes 148.5 kg/ha if no moisture stress occurred and 80.5 kg/ha when five moisture stress days occurred. For ten moisture stress days the optimum rate of N drops to 12 kg/ha.

The economic optimum rate of P fertilization can be calculated similarly, and is given by Equation 16:

$$\frac{dY}{dP} = 6.22 - 0.111\ p - 0.099\ ni_1 - 2(0.0166)\ P = \frac{Cp}{V} \quad (16)$$

where

the average p value = 9.4 ppm,

the average ni_1 value = 14.25 ppm,

Cp = 0.478 $/kg, and

$\frac{Cp}{V} = 5.83.$

It can be visualized from Equation 16, that even with the lowest amount of p and ni_1 in the soil, any P application to this soil will be uneconomical at the actual levels of cost and returns.[1]

For the group of soils with more than 25% clay in the B horizon the interaction between applied N and applied P was significant, so the rate of N and P which maximizes the profits is given by:

[1]The price of wheat and the cost of the fertilizers considered here were the average market prices for May 1977 in the Buenos Aires Province.

$$\frac{dY}{dN} = 1.82 - 0.0935\ ni_1 - 0.077\ d + 0.82\ om$$
$$- 2(0.021)\ N + 0.016\ P = 4.51$$

and

$$\frac{dY}{dP} = 9.44 - 0.079\ d - 0.294\ p - 2(0.039)P$$
$$+ 0.016\ N = 5.83.$$

When ni_1, d, om and p were replaced by their corresponding averages and the above equations solved simultaneously for values of N and P. It was found that P applications are not economical when an average of 14 moisture stress days occur and the soil has an average of 7.7 ppm of available phosphorus. Then if the amount of applied P = 0, the rate of nitrogen which produces the maximum profit is 32 kg/ha. However, if no moisture stress occurs, and the amount of p in the soil is at the minimum value (2.7 ppm), the economic optimum rate of fertilization is obtained with 15 kg of N and 33 kg of P_2O_5 per ha, provided that om and ni_1 are at their average group level.

CHAPTER V. CONCLUSIONS

The results obtained clearly demonstrate the high dependency of the yield response to fertilizers on moisture stress.

The number of stress days were significantly correlated with the check yields, with the response to N (b_1 coefficients), and with the response to P (b_3 coefficients).

Of the four individual rainfall periods correlated, the rainfall between booting and milky stage, R_3, showed the highest association with the check yields and with the response to nitrogen (b_1N). When two of the single rainfall periods were combined, R_{23} attained the highest correlation with check yields and was very close to total rainfall. R_1 and R_{34} were also significantly correlated with the response to N. However, since the stress index condensed the soil moisture information from heading to maturity into one value, the variables R_3, R_4, R_{34} and TR were highly correlated with d. For this reason when d was included in the model, the above mentioned rainfall periods were left out. The number of years since the last natural, temporary or permanent pasture (re) was highly correlated with the response to nitrogen fertilization. The amount of nitrates present in the soil at seeding from 0 to 20 cm and from 0 to 50 cm was significantly correlated with the response to N (b_1N).

The division of the 70 sites into two groups, according to the percent of clay present in the B horizon, allowed the soils of the same suborder to be grouped separately. The clay percentage of the B horizon of the coarse textured group showed a significant interaction with the rates of nitrogen fertilizer added.

The interaction between N and P was not significant for the coarse textured soils but was significant for the fine textured ones. The response to P fertilization was significantly correlated with the number of moisture stress days, $r = -0.21^{***}$, and with the amount of phosphorus present in the soil, $r = -0.30^{*}$, throughout the seventy experimental sites. Nevertheless, the interaction term Pp was significant only in the regression equation obtained for the fine textured soils. The economic analysis showed that any P application to a coarser textured soil will be uneconomical at the actual levels of cost and returns. The rate of nitrogen which maximizes profit in this group of soils depends mainly on the number of moisture stress days and on the clay percentage of the B horizon. The amount of nitrates present at seeding time has a comparatively small influence on the determination of the economic optimum rate of N.

For the fine textured soils the economic optimum rate for nitrogen depends on the organic matter content of the A horizon, the amount of nitrates present at seeding time from 0 to 20 cm, the number of moisture stress days, and the amount of P being applied. Similarly the economic optimum rate of P depends on the amount of available phosphorus in the soil, the number of moisture stress days, and the amount of N being applied. It was found that when an average of 14 moisture stress days occurs and when the amount of available phosphorus in the soil averages 7.7 ppm, the application of P fertilizers is uneconomical. This is in agreement with previous investigations. However, if the amount of available phosphorus in the soil is at its minimum level (2.7 ppm) and no water stress occurs, the economic optimum is obtained with 33 kg of P_2O_5 and 15 kg of N per ha, provided that the organic matter content and the amount of nitrates at seeding time are at their average levels.

It can be concluded that the soils with less than 25% clay in the B horizon have a better yielding potential than the fine textured ones, but it is also noticeable that high rates of nitrogen fertilization have to be supplied to these soils in order to attain maximum yields. The recommendations of P fertilizers have to be done carefully taking into account the value of available P, the possibilities of water stress, the organic matter content of the surface horizon, and the clay content of the solum because at the actual prices of wheat and P fertilizer the marginal returns are very low.

By examining the residual values ($Y-\hat{Y}$) for each of the proposed equations, it can be concluded that the postulated models can satisfactorily predict the variation in yield. Furthermore, almost all the predictor variables employed can be measured before seeding time or estimated from past records. Hence the postulated models become useful tools in the prediction of fertilizer needs throughout the area. Even though many relationships have been reasonably quantified by the postulated models, several others remain uncertain. For example, the selected stress index satisfactorily explained 33% of the observed variation in the yield of the check plot throughout the area. Its interaction with the responses to nitrogen and phosphorus were significant in all the yield prediction equations. Hence, it will be interesting to assess its effect on the response to the second application of nitrogen. The present data indicate a possible relationship between the effectiveness of the second N application and the number of stress days. Probably the date of occurrence of the stress is also important and has to be weighted. However, the analyzed experiments were not designed to provide this information and further research on this possibility has to be done.

The measurement of additional soil physical properties, such as soil moisture at earlier stages of the crop, hydraulic conductivity, soil porosity, and drainage is considered indispensible if better estimation of the nitrogen (NO_3^-) dynamics in the soil profile is desired. Even though the stability index used to express the resistance of aggregation to wet sieving showed a significant correlation with the response to P fertilization and with five uncontrolled variables (om, tn, ca, cb and npl), the obtained coefficients were always lower than expected. It is the belief of the author that the elimination of the finer fraction (0-2 mm) in the computation of the index would yield more accurate results.

A deeper sample for the estimation of available P, perhaps in the boundaries of the A_3 or B_1 horizon, 25-40 cm, could improve the prediction of yield response to phosphorus fertilization.

The influence of seeding time on yield for the same variety in a given county must be reassessed, because the new varieties used by the farmers may have slightly different cycles than the traditional ones. This could improve the yield predictions for a given area.

In order to be able to supply adequate information to the farmer regarding the economics of N and P fertilization, it is considered indispensible that rainfall probabilities for each area be calculated from past records.

The weed control done by farmers at the experimental sites was not satisfactory because the observations indicated an average of 6 to 8% of the plot areas were infested with weeds. It was also shown by the proposed models that a 5% infestation of the cropped area can produce a yield reduction of 114 kg of wheat per ha on soils with more than 25% clay, and that its interaction with moisture stress could produce a yield reduction of 295 kg/ha when 10 moisture stress days occur on the coarser soils.

Finally, if better yield predictions are desired, the measurement of incoming solar radiation or net radiation, during the grain filling period, is recommended for two or three areas at least within each county.

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APPENDIX

The scale used to quantify the degree of weed infestation was as follows:

0 = no weeds were observed

1 = less than 5% of the plot area was infested

2 = 5-10% of the plot area was infested

3 = 10-15% of the plot area was infested

4 = 25-50% of the plot area was infested

5 = more than 50% of the plot area was infested

The variable L (number of years since last legume crop), did not show a range broad enough to be included in the analysis. The crop history for each site was not precise, due to the fact that several farmers were new owners or new lessees and did not have enough years of crop history information to produce a uniform index. Even in the case of those with long crop history records, the number of years since the last legume crop did not show an appreciable variation. A secondary index called REST (re), which represents the number of years since the last natural, temporary or permanent pasture was adopted.

Table 5. Linear correlations among pairs of site variables (n=70)

	Y	pH	p	om	tn	ca	cc	st	TR
Y	1.00	0.07	-0.17	0.14	0.10	0.14	0.28*	0.02	0.24*
pH		1.00	-0.07	-0.45**	-0.34**	0.18	-0.10	-0.07	0.20
p			1.00	-0.22***	-0.38**	-0.30*	-0.29*	0.26*	0.21***
om				1.00	0.82**	0.39**	0.64**	-0.33**	0.09
tn					1.00	0.34**	0.60**	-0.43**	-0.03
ca						1.00	0.64**	-0.24*	0.14
cc							1.00	-0.25*	0.31**
st								1.00	-0.15
TR									1.00
d									
f									
w									
cb									
so									
tb									
R_1									
R_2									
R_3									
R_4									
ni									
ni_1									
ni_2									
ni_3									
nt_1									
nt_2									
nt_3									
npl									
tnp									
ta									
re									
R_{12}									
R_{23}									
R_{34}									

*Significant at the 5% level.

**Significant at the 1% level.

***Significant at the 10% level.

d	f	w	cb	so	tb	R_1	R_2
-0.53**	0.15	-0.21***	-0.11	-0.00	0.31**	0.04	0.13
0.00	0.30*	0.05	-0.24*	-0.37**	0.17	0.10	0.48**
0.06	0.08	-0.04	-0.27*	0.26*	-0.04	-0.06	0.26*
-0.23***	-0.35**	0.02	0.50**	0.16	-0.07	0.40**	-0.54**
-0.18	-0.45**	0.05	0.46**	0.09	0.01	0.40**	-0.64**
-0.11	0.15	0.04	0.52**	-0.31**	-0.19	0.49**	-0.21***
-0.45**	-0.17	0.15	0.37**	0.05	-0.02	0.50**	-0.35**
0.03	0.24*	-0.09	-0.22***	-0.04	0.05	-0.19	0.13
-0.59**	0.04	0.25*	-0.05	0.11	0.24*	0.49**	0.39**
1.00	0.00	-0.08	0.07	-0.22***	-0.42**	-0.27*	-0.04
	1.00	-0.05	-0.15	-0.15	0.11	-0.24*	0.42**
		1.00	0.18	-0.13	-0.09	-0.04	0.03
			1.00	-0.30**	-0.59**	0.18	-0.40**
				1.00	0.38**	-0.03	-0.09
					1.00	0.16	0.16
						1.00	-0.22***
							1.00

Table 5 (Continued)

	R_3	R_4	ni	ni_1	ni_2	ni_3	nt_1
Y	0.20***	0.11	0.24***	0.02	0.01	0.04	-0.04
pH	-0.17	-0.21***	-0.43**	-0.25*	-0.15	-0.24***	-0.40**
p	-0.07	0.17	0.15	0.03	0.22***	0.18	0.31*
om	0.29*	0.30*	0.49**	0.40**	-0.22***	0.07	-0.02
tn	0.19	0.25*	0.31*	0.20***	-0.37**	-0.17	-0.18
ca	0.11	0.03	-0.20	0.03	-0.28*	-0.18	-0.46**
cc	0.46**	0.29*	0.24***	0.18	-0.29*	-0.09	-0.28*
st	-0.14	-0.18	0.02	-0.16	0.18	0.03	0.22
TR	0.48**	0.65**	0.32*	0.09	-0.27*	-0.10	-0.05
d	-0.58**	-0.45**	-0.32*	0.00	0.28*	0.18	0.08
f	-0.12	-0.14	-0.29*	-0.15	-0.23***	0.10	-0.04
w	0.02	0.42**	0.23***	0.12	-0.09	0.02	0.08
cb	0.06	0.18	0.13	0.26*	-0.14	0.05	-0.06
so	0.21***	0.21***	0.32*	0.11	0.08	0.11	0.22***
tb	0.15	0.02	0.01	-0.02	-0.15	-0.12	-0.06
R_1	0.26*	0.16	0.02	0.09	-0.47**	-0.27*	-0.36**
R_2	-0.22***	-0.15	-0.09	-0.09	0.25***	0.15	0.28*
R_3	1.00	0.31**	0.15	-0.04	-0.14	-0.12	-0.23***
R_4		1.00	0.48**	0.23*	-0.29*	-0.08	0.00
ni			1.00	0.37**	0.11	0.28*	0.31*
ni_1				1.00	0.26*	0.72**	0.40**
ni_2					1.00	0.86**	0.52**
ni_3						1.00	0.59**
nt_1							1.00
nt_2							
nt_3							
npl							
tnp							
ta							
re							
R_{12}							
R_{23}							
R_{34}							

nt_2	nt_3	npl	tnp	ta	re	R_{12}
-0.03	-0.04	-0.00	0.15	0.08	-0.06	0.15
-0.33*	-0.39**	-0.31*	-0.30*	0.06	-0.26*	0.51**
0.28*	0.31*	0.20	0.25***	-0.27*	0.12	0.20***
-0.09	-0.06	0.48**	0.20	0.05	0.28*	-0.24*
-0.28*	-0.25***	0.20	-0.15	0.20***	0.39**	-0.33**
-0.38**	-0.45**	0.17	-0.08	-0.10	0.05	0.12
-0.19	-0.25***	0.25***	-0.01	0.09	0.21***	-0.00
0.20	0.22***	-0.23***	0.01	-0.16	-0.02	-0.00
-0.03	-0.05	0.47**	0.20	-0.01	0.11	0.67**
0.06	0.07	-0.17	0.01	-0.17	-0.26*	-0.21***
-0.06	-0.05	-0.09	0.03	0.14	-0.39**	0.23***
0.10	0.10	0.23***	0.17	-0.07	0.05	0.00
-0.13	-0.11	0.41**	0.07	-0.32**	0.00	-0.25*
0.13	0.19	0.22***	0.21	0.36**	0.23***	-0.10
-0.20	-0.13	-0.12	-0.04	0.53**	0.09	0.25*
-0.35**	-0.38**	0.28*	-0.27*	0.04	0.24*	0.44**
0.16	0.24***	-0.21	0.17	-0.03	-0.46**	0.77**
0.03	-0.11	0.17	0.02	0.03	0.26*	-0.04
-0.03	-0.01	0.67**	0.30*	-0.05	-0.36**	-0.03
0.25***	0.30*	0.52**	0.56**	-0.14	0.22	-0.09
0.24***	0.35**	0.52**	0.35**	-0.10	-0.14	-0.04
0.69**	0.65**	0.11	0.45**	-0.20	-0.34**	-0.05
0.62**	0.65**	0.35**	0.51**	-0.18	-0.35**	-0.01
0.73**	0.93**	0.25***	0.50**	-0.21	-0.23***	0.06
1.00	0.93**	0.19	0.55**	-0.32*	-0.19	-0.06
	1.00	0.24***	0.56**	-0.28*	-0.22***	0.00
		1.00	0.66**	-0.25***	0.16	-0.05
			1.00	-0.27*	-0.14	0.00
				1.00	-0.12	0.01
					1.00	-0.26*
						1.00

Table 5 (Continued)

	R_{23}	R_{34}
Y	0.23*	0.17
pH	0.39**	-0.23***
p	0.22*	0.09
om	-0.38**	0.36**
tn	-0.53**	0.27*
ca	-0.15	0.07
cc	-0.11	0.43**
st	0.05	-0.20***
TR	0.63**	0.71**
d	-0.33**	-0.60**
f	0.35**	-0.16
w	0.04	0.33**
cb	-0.36**	0.16
so	0.02	0.25*
tb	0.24*	0.08
R_1	-0.08	0.24*
R_2	0.86**	-0.21***
R_3	0.30*	0.69**
R_4	0.02	0.90**
ni	0.00	0.43**
ni_1	-0.11	0.16
ni_2	0.15	-0.28*
ni_3	0.07	-0.11
nt_1	0.12	-0.10
nt_2	0.18	-0.01
nt_3	0.16	-0.06
npl	-0.10	0.58**
tnp	0.18	0.23***
ta	0.00	-0.02
re	-0.31**	0.39**
R_{12}	0.74**	-0.04
R_{23}	1.00	0.15
R_{34}		1.00

Table 6. Linear correlation among regression coefficients and site variables

Variable	b_1N	b_3P
Y_{ch}	0.15	0.25*
pH	0.02	-0.08
p	-0.01	-0.30*
om	0.23***	0.25*
tn	0.24*	0.16
ca	0.02	0.10
cc	0.17	0.10
st	-0.07	-0.24*
TR	0.20***	0.12
d	-0.49**	-0.21***
f	-0.12	-0.06
w	-0.14	-0.04
cb	-0.14	0.29*
so	0.05	-0.12
tb	0.14	-0.04
R_1	0.22***	0.00
R_2	-0.10	0.04
R_3	0.24*	0.08

*Significant at the 5% level.

**Significant at the 1% level.

***Significant at the 10% level.

Table 6 (Continued)

Variable	b_1N	b_3P
R_4	0.15	0.14
ni	0.08	0.40**
ni_1	-0.22***	0.22***
ni_2	-0.21	0.02
ni_3	-0.28*	0.18
nt_1	-0.18	0.04
nt_2	-0.06	0.02
nt_3	-0.13	0.04
npl	-0.04	0.43**
tnp	-0.14	0.32*
ta	0.20***	-0.18
re	0.40**	-0.01
R_{12}	0.04	0.03
R_{23}	0.02	0.07
R_{34}	0.23***	0.14

Table 7. Average treatment yields[a] for 1972

Site #	0-0	0-50	0-100	25-25	25-50	25-75	50-0	50-50	50-100	75-25	75-75	100-0	100-50	100-100
2010	2148	2488	2636	2503	2591	2813	2370	2872	2902	2592	2813	2296	2858	2725
2020	1768	2391	2321	2367	2498	2451	1805	2205	2405	2381	2660	1838	2367	2498
2030	3400	3700	3724	3724	4014	3584	3494	3884	3814	3704	3644	3544	3904	3684
2040	2323	2401	2141	2323	2583	2609	2323	2609	2192	2375	2713	2358	2323	2427
2050	2411	2922	3081	2984	3089	3219	2566	3089	3130	2686	3258	2353	3061	3158
2060	2464	3201	3381	2860	3397	3464	2769	2894	3241	2950	3339	2741	3297	3228
2070	1680	2089	2217	1880	2186	2330	1960	2721	2772	2469	2926	2310	3080	3130
2080	2812	2777	2974	2847	2928	2777	2997	3171	2997	3050	3032	3240	3217	2928
2100	2324	2460	2500	2486	2541	2595	2296	2718	2609	2459	2487	2269	2500	2623
2120	1893	1945	1965	2058	2086	2140	2418	2572	2294	2829	2850	3478	3056	3282
2130	1854	1950	2031	2292	2229	2365	2615	2635	2656	2958	3073	3104	3156	3354
2140	1993	2100	2197	2197	2210	2414	2031	2465	2500	2147	2401	2057	2337	2605
2150	2043	2434	2684	2608	2717	2891	2184	2825	3043	2728	2956	2238	3065	3565

[a] in kg/ha.

Table 8. Average treatment yields[a] for 1973

Site #	0-0	30-0	60-0	90-0	0-30	30-30	60-30	90-30	0-60	30-60	60-60	90-60	0-90	30-90	60-90	90-90
3011	1333	1146	1083	937	1396	1250	979	1125	1541	1325	1041	896	1229	1187	1000	1125
3020	1600	1350	1240	1460	1840	1600	1640	1790	1800	1850	1850	1890	2081	1920	2160	1830
3041	2133	2000	2044	2000	2577	2477	2377	2155	2577	2266	2377	2066	2622	2466	2222	2110
3050	1239	1331	1343	1193	1587	1424	1436	1505	1599	1668	1564	1459	1749	1564	1691	1737
3062	1751	1761	1460	1543	1807	1761	1761	1807	1807	1877	1946	1957	1946	1993	2023	2132
3071	1273	1500	2000	1909	1477	1522	1659	2091	1350	1464	1582	1909	1409	1682	1772	2000
3080	2360	2462	2452	2388	2277	2546	2551	2518	2388	2638	2545	2351	2416	2551	2517	2805
3091	2479	2525	2641	2711	2644	2757	2479	2386	2850	2132	2572	2641	2618	2572	2688	2224
3101	1071	1178	1250	1078	1214	1250	1250	1250	1071	1214	1214	1107	1214	1214	1071	1393
3110	2341	2340	1759	1798	1984	2235	2142	2129	2248	2380	1838	1798	2275	2407	1930	1864
3120	1979	2071	2175	2199	1990	2285	2372	2615	2001	2303	2453	2824	2025	2305	2592	2685
3131	1626	1668	1772	1709	1918	1918	1726	1709	1772	1849	1813	1751	1918	2001	1793	1855
3140	1273	1573	1724	1574	1215	1493	1608	1736	1458	1678	1817	1759	1307	1481	1712	1978
3180	1813	1889	1893	1912	1932	2035	1991	1980	2009	2009	2000	2118	2079	2265	2227	2164
3190	1222	1464	1333	1339	1402	1405	1439	1592	1293	1382	1581	1689	1376	1431	1581	1584
3201	2185	2481	2500	2500	2722	2496	2593	2556	2500	2519	2593	2685	2463	2556	2593	2556
3210	1010	1416	1552	1283	1449	1618	1600	1615	1477	1711	1654	1592	1467	1617	1676	1896
3221	1364	1458	1354	1271	1563	1625	1583	1771	1833	1646	1958	1729	1796	1833	1771	1799
3230	2002	2292	2187	2164	2245	2256	2280	2349	2200	2407	2511	2002	2176	2276	2315	2303

[a] in kg/ha.

Table 8 (Continued)

Site #	0-0	30-0	60-0	90-0	0-30	30-30	60-60	90-90	0-60	30-60	60-60	90-60	0-90	30-90	60-90	90-90
3240	1522	2088	2122	2333	1600	1600	1666	2188	1411	1699	1855	1855	1266	1500	1633	2417
3260	2204	2109	2119	1934	2201	2207	2222	2294	2037	2397	2448	2260	2325	2448	2487	2530
3270	1636	2037	2182	1997	1952	1981	2210	2466	1898	2165	2388	2418	2111	2089	2130	2411
3280	1875	2188	2245	1713	2003	1979	2037	2384	1887	2064	2083	2002	1933	1991	2002	2373
3290	1830	1644	1697	1645	1786	1906	1841	1919	1884	1840	1800	1895	1961	1971	2000	2045
3301	1556	1911	1956	2022	1733	1956	2044	1844	1778	2140	2144	2133	1803	1988	2178	2222
3320	2094	2156	2219	2062	2406	2458	2490	2323	2396	2547	2583	2522	2439	2433	2541	2452
3330	1750	2330	2132	2206	1851	1942	2004	2210	1759	2235	2296	2232	1964	2049	2094	2431
3360	1776	2069	2152	2137	2019	2263	2343	2400	2036	2245	2379	2530	2025	2165	2234	2248
3370	1627	1493	1373	1639	1687	1801	1750	1650	1644	1706	1657	1678	1785	1701	1685	1504
3380	2803	2578	2421	2580	2700	3084	2923	2649	3128	3116	2997	2833	2992	3426	2935	2678
3390	2349	2360	2385	2036	2391	2521	2490	2489	2823	2784	2483	2467	2575	2705	2651	2478
3400	2088	2216	2121	2055	2129	2065	1940	2078	1887	2360	1890	1949	2107	2110	2190	2018
3410	2085	2496	2335	2293	2328	2525	2604	2875	2474	2641	2891	2960	2515	2819	2813	3089
3420	2033	2117	2150	1908	2626	2603	2600	2593	2510	3056	2775	2718	2715	2921	2927	2997
3430	1226	1342	1214	1235	1311	1438	1376	1264	1507	1365	1363	1299	1391	1497	1347	1668

Table 8 (Continued)

Site #	0-0	15-0	30-0	45-0	0-30	15-30	30-30	45-30	0-60	15-60	30-60	45-60	0-90	15-90	30-90	45-90
3012	1479	1354	1229	1229	1541	1375	1291	1354	1583	1312	1291	1354	1562	1479	1416	1291
3042	1711	1733	1689	1555	1977	1866	2022	1733	2066	1844	1985	2022	1755	1822	1933	1933
3061	1483	1640	1668	1436	1622	1761	1691	1274	1599	1675	1807	1714	1714	1714	1714	1761
3102	1143	1071	1071	1143	1036	1107	1071	1071	1071	1143	1214	1286	1107	1178	1286	1214
3202	2296	2519	2481	2222	2283	2532	2648	2741	2444	2630	2630	2704	2556	2494	2556	2370
3222	1521	1938	1417	1396	2021	1688	1729	1604	1792	1708	1667	1854	2438	1667	2167	1896
3302	1722	1744	1833	1944	1750	2083	2056	1806	1722	1778	1861	2222	1821	2056	2112	2167

Table 9. Average treatment yields[a] for 1974

Site #	0-0	30-0	60-0	90-0	0-30	30-30	60-30	90-30	0-60	30-60	60-60	90-60	0-90	30-90	60-90	90-90
4021	2368	2607	1928	2071	2143	1678	2678	2464	2499	3035	3071	3213	2678	2785	2928	3071
4031	1801	1812	1850	2125	1791	1887	1929	2083	1437	1979	1987	2083	1841	1958	1999	2125
4041	2570	2572	2653	2788	2467	2600	3087	2900	2816	3033	3033	2951	2998	3416	3369	3366
4051	1138	1080	1055	1138	1055	1166	1055	1055	1277	1333	1416	1416	1250	1025	1111	1200
4071	1156	1291	1366	1385	1333	1342	1350	1387	1083	1437	1308	1291	1270	1270	1304	1375
4081	2220	2225	2274	2143	2572	2712	2518	2449	2296	2537	3062	2865	2799	2821	3018	2887
4091	1985	2084	2090	2131	1925	2200	2276	2131	2222	2359	2374	2589	2206	2245	2314	2543
4101	1708	1750	2166	2291	2020	2166	2200	2270	1708	1812	2125	2278	1979	2104	2283	2416
4111	1562	1729	1804	2020	1916	1916	2125	2250	1854	2041	2176	2300	1791	2208	2566	2624
4131	2375	2254	2254	2377	2746	2664	2664	2787	2828	2951	2992	2664	2541	2828	2966	2910
4141	2968	2933	2930	3028	2589	3225	3252	3175	2859	2859	3055	3175	2784	2951	3250	3126
4161	2284	2456	2283	2270	2557	2701	2686	2643	3088	3060	3045	3103	2758	2758	2959	2988
4171	1803	1824	1883	1906	1947	1985	2049	1967	2254	2293	2316	2131	2295	2267	2172	2172
4191	2457	2577	2606	2514	2681	2989	2787	2769	2876	3109	3227	2834	2461	2813	2857	2813
4211	1741	1626	1710	1814	2148	2085	1968	1939	2559	2544	2627	2002	2231	2148	1897	1960

[a]in kg/ha.

Table 10. Average treatment yield increments, $\Delta Y = Y - Y_{(ch)}$, kg/ha

Site # / Treat.	2010	2020	2030	2040	2050	2060	2070	2080	2100	2120	2130	2140	2150
0-50	340	623	300	78	511	737	409	-35	136	52	96	107	391
0-100	488	553	324	-182	670	917	537	162	176	72	177	204	641
25-25	355	599	324	0	573	396	200	35	162	165	438	204	565
25-50	443	730	614	260	678	933	506	116	217	193	375	217	674
25-75	665	683	184	286	808	1000	650	-35	271	247	511	421	848
50-0	222	37	194	0	155	305	280	185	-28	525	761	38	141
50-50	724	437	484	286	678	430	1041	359	394	679	781	472	782
50-100	754	637	414	-131	719	777	1092	185	285	401	802	507	1000
75-25	444	613	304	52	275	486	789	238	135	936	1104	154	685
75-75	665	892	244	390	847	875	1246	220	163	957	1219	408	913
100-0	148	70	144	35	058	277	630	428	-55	1585	1250	64	195
100-50	710	599	504	0	650	833	1400	405	176	1163	1302	344	1022
100-100	577	730	284	104	747	764	1450	116	339	1389	1500	612	1522

Table 10 (Continued)

Treat. \ Site #	3011	3020	3041	3050	3062	3071	3080	3091	3101	3110	3120	3131	3140
30-0	-187	-250	-133	92	10	227	102	46	107	-01	92	42	300
60-0	-250	-360	-089	104	-291	727	92	162	179	-582	196	146	451
90-0	-396	-140	-133	-46	-208	636	28	232	07	-543	220	83	301
0-30	63	240	444	348	56	204	-83	165	143	-351	11	292	-58
30-30	-83	0	344	135	10	249	186	278	179	-106	306	292	220
60-30	-354	40	244	197	10	386	191	0	179	-199	393	100	335
90-30	-208	190	82	266	56	818	150	-93	179	-212	636	83	463
0-60	208	200	444	360	56	77	28	371	0	-093	22	146	185
30-60	-008	250	133	429	126	191	278	-347	143	39	324	223	405
60-60	-292	250	244	325	195	409	185	93	143	-503	474	187	544
90-60	-437	290	-067	220	206	636	-09	162	36	-351	845	125	486
0-90	-104	481	489	510	195	136	56	139	143	-66	46	292	34
30-90	-146	320	333	325	242	409	191	93	143	66	326	375	208
60-90	-333	560	89	452	272	499	157	209	0	-411	613	167	439
90-90	-208	230	-23	498	381	727	445	-235	322	-477	706	229	705

Table 10 (Continued)

Site # Treat.	3180	3190	3201	3210	3221	3230	3240	3260	3270	3280	3290	3301	3320
30-0	76	242	296	406	94	290	566	-95	401	313	-186	355	62
60-0	80	111	315	542	-10	185	600	-85	546	370	-133	400	125
90-0	99	117	315	273	-93	162	811	-270	361	-162	-185	466	-32
0-30	119	180	537	439	199	243	78	-03	316	128	-44	177	312
30-30	222	183	311	608	261	254	78	03	345	104	76	400	364
60-30	178	217	408	590	219	278	144	18	574	162	11	488	396
90-30	167	370	371	605	407	347	666	90	830	509	89	288	229
0-60	196	71	315	467	469	198	-111	-167	262	12	54	222	302
30-60	196	160	334	701	282	405	177	193	529	189	10	584	453
60-60	187	359	408	644	494	509	333	244	752	208	-30	588	489
90-60	305	467	500	532	365	0	333	56	782	127	65	577	428
0-90	266	154	278	457	432	174	-256	121	475	58	131	247	345
30-90	452	209	371	607	469	274	-22	244	453	116	141	432	339
60-90	414	359	408	666	407	313	111	283	494	127	170	622	447
90-90	351	362	371	886	435	301	955	326	775	498	215	666	360

Table 10 (Continued)

Site # Treat.	3330	3360	3370	3380	3390	3400	3410	3420	3430	4021	4031	4041	4051
30-0	580	293	-134	-225	11	128	411	84	116	239	11	2	-58
60-0	382	376	-254	-382	36	33	250	117	12	-440	49	83	-83
90-0	456	361	12	-223	-313	-33	208	-125	9	-297	324	218	45
0-30	101	243	60	-103	42	41	253	593	85	-225	-10	-103	-83
30-30	192	487	174	281	172	-23	440	570	212	310	86	30	28
60-30	254	567	123	120	141	-148	519	567	150	310	128	517	-83
90-30	460	624	23	-154	140	-10	790	560	38	96	282	330	-83
0-60	9	260	37	325	474	-201	389	477	281	131	-364	246	139
30-60	485	470	79	313	135	272	556	1023	139	687	178	463	195
60-90	546	603	30	194	134	-198	806	742	137	703	186	463	278
90-60	482	754	51	30	118	-139	875	685	73	845	282	381	278
0-90	214	249	158	189	226	19	430	682	165	310	40	428	112
30-90	299	389	74	623	356	22	734	888	271	417	157	846	-113
60-90	344	458	58	133	302	102	728	894	121	560	198	799	-27
90-90	681	472	-123	-125	129	-70	1004	964	-158	703	324	796	62

Table 10 (Continued)

Treat.	Site # 4071	4081	4091	4101	4111	4131	4141	4161	4171	4191	4211
30-0	135	05	99	42	167	-121	-35	172	21	120	-115
60-0	210	54	105	453	242	-121	-38	-01	80	149	-31
90-0	229	-77	146	583	458	02	60	-14	103	57	73
0-30	177	352	-60	312	354	371	-379	273	144	224	407
30-30	186	492	215	458	354	289	257	417	182	532	344
60-30	194	298	291	292	563	289	284	402	246	330	227
90-30	231	229	146	562	688	412	207	359	164	312	198
0-60	-73	76	237	0	292	453	-109	804	451	419	818
30-60	281	317	374	104	479	576	-109	776	490	652	803
60-60	152	842	389	417	614	617	87	761	513	770	886
90-60	135	645	604	570	738	289	207	819	328	377	261
0-90	144	579	221	271	229	166	-184	474	492	4	490
30-90	114	601	260	396	646	453	-17	474	464	356	407
60-90	148	798	329	375	1004	591	282	675	369	400	156
90-90	219	667	558	708	1062	535	158	704	369	356	219

Table 10 (Continued)

Site # Treat.	3012	3042	3061	3102	3202	3222	3302
15-0	-125	22	157	-72	223	417	22
30-0	-250	-22	185	072	185	-104	111
45-0	-250	-156	-47	00	-74	-125	222
0-30	62	266	139	-107	537	500	28
15-30	-104	155	278	-36	56	167	361
30-30	-188	311	208	-72	352	208	334
45-30	-125	22	-209	-72	445	83	84
0-60	104	355	116	-72	148	271	00
15-60	-167	133	192	00	334	187	56
30-60	-188	274	324	71	334	146	139
45-60	-125	311	231	143	408	333	500
0-90	83	44	231	-36	260	917	99
15-90	00	111	231	35	148	146	334
30-90	-63	222	231	143	260	646	390
45-90	-183	222	278	71	74	375	445

Table 11. Values of the measured uncontrolled variables at each site

Site # \ Variable	cb	tb	so	st	R_1	R_2	R_3	R_4	TR	d	w	f	L	re
2010	20.4	30	60	1.46	26	226	12	59	323	13	0	16	6	0
2020	28.2	35	70	0.69	26	226	12	59	323	10	5	8	6	0
2030	20.1	60	100	2.05	19	219	18	83	339	4	0	36	6	0
2040	21.0	60	100	1.77	77	183	60	56	376	0	4	24	6	6
2050	41.3	30	100	1.10	31	212	57	27	327	5	0	19	1	1
2060	24.1	40	100	0.95	31	212	57	27	327	6	0	19	-	-
2070	40.7	35	85	1.35	136	100	106	33	375	0	3	23	6	3
2080	34.6	35	70	1.32	137	130	48	10	325	12	0	15	6	0
2100	38.6	32	80	1.35	132	78	34	9	253	17	0	12	6	1
2120	21.3	60	100	7.25	151	140	43	13	347	0	0	9	6	6
2130	20.7	60	100	1.31	151	189	53	72	465	0	1	7	6	6
2140	35.0	35	80	1.35	197	142	36	9	384	10	2	27	6	2
2150	33.4	35	100	1.34	55	143	34	0	232	0	0	19	6	0
3011	27.2	35	100	1.77	52	168	14	22	256	30	1	12	6	2
3012	27.2	35	100	1.77	52	168	14	22	256	30	1	12	6	2
3020	36.0	25	55	0.69	46	141	13	7	207	22	4	22	6	0
3041	38.0	35	60	1.80	35	162	19	16	242	21	3	18	6	0
3042	38.0	35	60	1.80	35	162	19	16	242	21	3	18	6	0
3050	18.8	50	80	1.42	37	134	30	0	201	22	1	14	6	6

Table 11 (Continued)

Variable Site #	pH	om	tn	ca	ta	cc	p	n_i	ni_1	ni_2				
2010	6.7	1.7	.097	12.1	30	14.1	10.5		13.5					
2020	6.8	3.1	.181	25.6	25	24.9	8.5		14.0					
2030	6.8	2.8	.143	21.2	35	22.2	13.6		14.5					
2040	6.5	3.0	.151	20.0	25	18.8	11.4		14.5					
2050	6.6	3.5	.174	24.6	30	22.7	5.8		17.5					
2060	6.1	3.6	.187	19.8	35	28.3	7.8		13.0					
2070	6.3	4.7	.240	34.4	30	38.9	4.6		14.5					
2080	6.4	5.5	.276	27.3	25	31.6	7.2		19.0					
2100	6.1	5.3	.260	30.3	25	31.6	5.4		19.0					
2120	6.6	2.3	.120	20.0	25	21.5	22.5		18.0					
2130	6.4	3.1	.165	21.4	30	23.9	10.8		19.0					
2140	6.5	5.0	.245	31.8	35	33.3	7.7		13.0					
2150	6.3	3.9	.209	27.2	30	29.3	3.2		17.5					
3011	6.1	2.4	.153	20.7	25	20.0	11.0	30.9	16.3	6.0	13.8	3.0	430	3.18
3012	6.2	2.2	.147	20.7	25	20.0	11.0	31.5	15.9	6.3	13.8	3.0	430	3.18
2030	6.5	2.5	.167	22.6	25	20.0	9.5	33.9	19.3	9.7	18.0	5.2	390	2.99
3041	6.5	2.5	.198	21.2	25	20.0	4.2	42.3	16.3	22.2	14.4	12.4	570	3.56
3042	6.4	2.5	.179	21.2	25	20.0	4.7	49.8	20.8	20.4	14.4	12.4	570	3.56
3050	6.7	2.7	.163	19.3	22	17.5	3.8	36.6	7.7	11.2	8.1	3.0	290	2.99

Table 11 (Continued)

Variable Site #	cb	tb	so	st	R_1	R_2	R_3	R_4	TR	d	w	f	L	re
3061	28.2	30	100	1.60	24	139	0	6	169	17	2	10	6	2
3062	28.2	30	100	1.60	24	139	0	6	169	17	2	10	6	2
3071	27.5	30	100	2.05	32	140	21	6	197	22	1	16	6	6
3080	18.8	60	100	1.76	45	198	50	18	311	8	0	22	6	2
3091	21.8	60	100	1.70	9	143	31	23	206	10	1	32	6	0
3101	32.9	35	80	1.35	34	144	2	39	219	20	4	14	6	0
3102	32.9	35	80	1.35	34	144	2	39	219	20	4	14	6	0
3110	28.5	40	100	1.30	10	190	0	19	219	20	3	22	6	3
3120	29.7	35	100	0.95	22	155	28	0	205	17	1	26	4	4
3131	36.9	40	80	0.92	30	160	5	39	234	19	3	26	6	0
3140	24.0	35	100	1.60	32	140	21	4	197	17	2	20	6	0
3180	37.9	35	70	1.44	103	43	25	20	191	17	2	12	6	3
3190	40.5	40	100	1.35	88	82	46	38	255	11	2	12	6	6
3201	37.0	35	65	1.57	55	74	44	5	173	17	1	20	6	1
3202	37.0	35	65	1.57	55	74	44	5	178	17	1	20	6	1
3210	25.9	45	100	1.21	55	73	26	5	158	19	1	12	6	3
3221	34.0	25	100	1.30	65	67	43	12	187	28	2	14	1	1
3222	34.0	25	100	1.30	65	67	43	12	187	28	2	14	1	1
3230	23.9	35	100	0.96	67	75	27	69	238	18	1	16	6	6

Table 11 (Continued)

Site #	ph	om	tn	ca	ta	cc	p	ni	ni_1	ni_2	nt_1	nt_2	npl	tnp
	Variables													
3061	5.8	3.30	.210	17.2	24	20.0	8.8	46.2	24.9	31.2	5.9	27.6	401	3.50
3062	5.8	3.30	.193	17.2	25	20.0	14.2	41.1	25.1	35.7	45.9	27.6	401	3.50
3071	5.9	3.27	.203	19.0	30	17.5	21.8	45.5	10.6	10.5	9.3	3.2	320	2.94
3080	6.5	3.00	.197	22.6	35	18.8	11.4	46.6	8.8	14.4	11.4	3.0	418	3.21
3091	6.1	2.72	.124	20.3	35	22.5	7.2	41.5	38.4	26.7	25.6	8.1	1300	3.63
3101	6.4	3.80	.201	21.2	35	23.8	4.6	47.1	28.5	6.0	6.1	3.3	478	3.15
3102	6.4	4.15	.186	21.2	35	23.8	7.9	43.5	20.0	5.9	6.1	3.0	478	3.15
3110	6.3	2.77	.170	23.4	30	24.0	11.3	41.7	9.2	25.3	15.6	11.4	750	4.15
3120	6.3	2.25	.147	22.9	30	22.5	6.4	31.6	9.4	10.8	4.8	3.0	310	2.93
3131	6.7	4.40	.227	28.3	30	22.5	9.0	38.6	22.8	15.8	9.9	4.5	1270	4.02
3140	6.3	3.02	.179	17.4	35	20.0	7.4	30.7	11.8	9.7	7.9	5.1	298	3.06
3180	6.0	4.42	.298	23.6	30	28.8	4.4	36.7	10.0	11.5	3.0	3.0	249	2.68
3190	6.1	3.42	.238	23.9	35	20.0	2.7	30.4	8.0	5.5	1.3	0.6	270	2.04
3201	6.1	3.20	.205	25.2	30	22.5	3.4	29.1	10.0	14.7	1.5	2.2	368	2.97
3202	6.2	3.30	.209	25.2	30	22.5	3.9	19.1	12.0	17.1	1.5	2.2	368	2.97
3210	6.2	3.00	.199	15.1	40	18.8	6.5	32.2	7.6	12.9	3.0	3.0	165	2.39
3221	6.3	3.60	.162	24.0	25	23.8	10.7	39.9	31.0	28.0	3.2	12.0	1540	3.57
3222	6.3	3.60	.162	24.0	25	23.8	10.7	39.9	31.0	28.0	3.2	12.0	1540	3.57
3230	6.3	3.10	.221	25.7	35	23.8	4.6	40.6	8.8	22.5	3.0	9.6	1680	3.79

Table 11 (Continued)

Site #	cb	tb	so	st	R_1	R_2	R_3	R_4	TR	d	w	f	L	re
3240	37.8	30	75	2.22	41	60	23	13	137	12	2	20	6	6
3260	31.6	50	100	1.18	66	98	34	31	199	17	2	8	6	6
3270	20.8	60	100	1.28	90	39	18	22	170	13	3	16	6	6
3280	32.2	40	75	1.80	69	71	28	57	225	10	1	24	6	0
3290	24.9	65	100	0.69	79	82	28	57	246	10	2	14	6	0
3301	31.3	35	80	1.02	62	56	24	25	167	18	1	14	6	6
3302	31.3	35	80	1.02	62	56	24	25	167	18	1	14	6	6
3320	35.1	30	52	1.22	92	38	50	21	201	14	0	14	6	6
3330	28.8	40	100	0.61	86	37	76	16	215	14	1	4	6	6
3360	43.8	20	50	1.07	72	91	62	55	280	15	2	12	6	6
3370	38.5	35	100	0.60	104	46	46	26	221	14	0	12	1	1
3380	35.7	38	90	0.80	103	77	79	125	384	0	3	4	6	6
3390	35.6	44	100	1.32	64	76	98	79	317	0	3	9	6	6
3400	29.0	35	100	1.74	110	68	49	171	398	8	4	9	6	6
3410	34.3	40	100	1.20	93	64	66	113	335	2	2	6	6	6
3420	41.3	45	100	0.95	70	80	51	105	306	0	3	11	6	6
3430	45.5	27	100	0.63	113	115	61	329	618	5	5	20	6	6

Table 11 (Continued)

Variable / Site #	pH	om	tn	ca	ta	cc	p	ni	ni_1	ni_2	nt_1	nt_2	npl	tnp
3240	6.2	3.6	.226	28.4	30	30.0	6.5	32.8	7.7	5.5	0.9	1.9	155	1.97
3260	6.3	4.3	.295	19.6	35	25.0	5.2	38.9	8.5	12.9	4.9	2.8	705	3.01
3270	6.4	4.5	.319	21.6	40	26.3	2.8	42.6	15.5	5.5	1.6	0.9	215	2.44
3280	6.3	3.1	.215	25.6	35	26.3	8.5	26.2	14.5	5.5	1.7	0.6	255	2.34
3290	6.4	2.4	.215	25.6	35	27.5	5.8	26.8	12.1	7.2	1.7	1.2	700	3.24
3301	6.3	4.2	.261	23.3	30	20.0	7.3	15.5	16.3	5.9	3.1	3.1	190	2.30
3302	6.2	3.9	.257	23.3	30	20.0	10.5	28.8	11.5	6.3	3.0	3.0	190	2.30
3320	6.6	3.7	.223	30.0	15	27.5	3.5	27.1	17.2	7.4	3.4	10.5	1110	3.07
3330	6.3	4.4	.314	22.2	40	30.0	6.4	33.7	17.0	11.1	3.0	3.0	315	2.62
3360	6.5	4.0	.257	30.0	20	30.0	7.7	45.1	20.6	11.8	3.3	3.1	1130	3.22
3370	6.3	4.2	.278	25.0	35	25.0	3.6	40.9	22.8	8.7	7.5	3.0	515	2.70
3380	6.2	4.5	.277	22.8	28	28.0	7.4	50.7	23.8	6.4	2.2	1.7	830	3.01
3390	5.8	5.1	.288	22.8	24	35.6	9.6	38.3	26.5	8.8	3.4	3.2	470	2.50
3400	6.3	4.6	.276	26.0	35	37.5	6.4	50.5	27.9	5.5	13.7	6.0	1370	3.07
3410	6.5	4.7	.303	23.0	30	33.1	5.6	53.6	16.8	5.5	2.4	1.5	700	2.97
3420	6.3	5.0	.323	24.3	30	35.1	6.0	48.4	23.9	9.9	10.2	3.0	2000	3.67
3430	5.9	4.7	.251	24.5	23	25.6	17.0	54.4	25.6	5.9	13.5	7.5	3770	3.96

Table 11 (Continued)

Site #	Variables cb	tb	so	st	R_1	R_2	R_3	R_4	TR	d	w	f	L	re
4021	30.2	40	100	1.60	47	105	71	61	284	5	2	10	6	3
4031	23.0	40	100	1.71	36	90	124	66	317	5	3	14	6	1
4041	30.4	40	100	1.40	31	86	126	65	308	0	1	18	6	2
4051	34.7	20	100	1.40	14	52	21	50	137	23	0	18	-	-
4071	36.5	25	100	2.00	10	43	23	48	124	21	1	16	6	6
4081	33.0	25	65	2.42	24	86	0	89	199	5	4	18	6	6
4091	32.1	40	100	1.53	25	60	72	80	237	9	2	16	5	5
4101	23.0	50	100	1.40	32	91	122	87	332	5	3	17	6	5
4111	35.0	25	80	1.40	21	117	71	50	239	10	2	16	6	4
4131	34.2	40	100	1.70	30	53	22	60	165	10	1	13	6	4
4141	29.5	30	100	1.05	32	35	25	78	170	5	2	9	6	5
4161	32.7	60	100	1.00	53	57	45	83	238	5	1	11	6	4
4171	48.8	30	100	1.40	56	26	27	46	155	15	2	4	6	2
4191	34.3	40	100	1.09	80	43	26	61	210	16	0	8	6	6
4211	35.0	40	100	1.60	99	31	60	110	282	13	2	10	6	6

Table 11 (Continued)

Site #	pH	om	tn	ca	ta	cc	p	ni	ni_1	ni_2	nt_1	nt_2	npl	tnp
	Variables													
4021	6.9	4.18	.221	18.6	25	25.4	4.6	57.6	11.3	13.2	6.7	14.0	562	3.54
4031	6.1	2.59	.136	16.2	30	22.8	13.0	35.0	8.5	13.8	23.4	25.3	1095	3.84
4041	6.0	4.38	.223	21.9	35	28.8	4.0	40.6	14.0	16.1	2.8	2.3	517	2.98
4051	5.9	4.32	.221	19.1	20	22.5	18.1	52.5	19.5	26.7	14.9	8.8	1275	3.44
4071	6.1	3.96	.202	21.5	25	23.0	13.0	45.0	15.9	15.7	14.7	10.5	1105	4.07
4081	6.2	2.60	.140	24.3	25	23.1	5.2	38.2	11.0	15.1	8.0	6.3	620	3.34
4091	6.2	3.22	.161	22.8	30	23.9	10.4	37.8	9.2	11.7	13.9	6.8	685	3.23
4101	6.1	4.14	.214	20.3	35	28.1	8.1	50.7	9.7	13.4	6.0	11.9	575	3.90
4111	5.8	3.88	.187	23.0	20	25.0	8.7	44.8	17.3	13.4	3.9	10.9	1020	3.52
4131	5.8	3.66	.264	19.5	30	19.7	5.1	58.3	17.9	9.2	14.8	6.7	641	3.33
4141	6.0	4.02	.263	22.6	25	27.7	9.8	62.4	11.1	8.1	7.7	5.1	695	3.38
4161	5.6	6.29	.329	21.2	40	26.5	4.2	58.5	44.7	16.3	23.3	12.2	1900	4.02
4171	5.9	5.84	.277	22.1	25	24.8	4.2	46.2	26.5	9.1	27.8	5.8	2525	3.98
4191	5.7	6.34	.283	28.8	30	29.5	9.6	47.0	18.2	7.4	8.9	8.5	1127	4.11
4211	5.5	5.42	.269	20.2	25	24.2	8.2	73.4	23.7	11.9	19.6	7.4	2837	4.15

Table 12. Observed range and mean values for each uncontrolled variable

Variable	Unit of measurement	Minimum value	Maximum value	Mean value
ca	%	12.10	34.40	22.84
cb	%	16.60	46.60	31.63
cc	meq/100 gr.	14.10	38.90	24.81
d	days	0.00	30.00	12.60
f	weeks	4.00	36.00	15.30
L	years	1.00	6.00	5.70
ni	ppm	15.50	73.40	41.20
ni_1	ppm	7.60	44.70	17.11
ni_2	ppm	5.50	35.70	12.96
ni_3	ppm	6.40	31.50	14.74
npl	ppm	155.00	3770.00	826.00
nt_1	ppm	0.90	45.90	9.93
nt_2	ppm	0.60	27.60	6.70
nt_3	ppm	0.90	34.90	7.99
om	%	1.70	6.30	3.73
p	ppm	2.70	22.50	8.09
pH	pH units	5.50	6.80	6.23
R_1	mm	9.00	197.00	60.58
R_2	mm	26.00	226.00	106.87
R_3	mm	0.00	126.00	39.84
R_4	mm	0.00	329.00	45.84
re	years	0.00	6.00	3.50

Table 12 (Continued)

Variable	Unit of measurement	Minimum value	Maximum value	Mean value
so	cm	50.00	100.00	89.81
st	index	0.60	2.42	1.38
ta	cm	15.00	40.00	29.46
tb	cm	20.00	65.00	38.30
tn	%	0.097	0.0329	0.216
tnp	%	1.97	4.15	3.23
TR	mm	124.00	618.00	252.00
w	0-5	0.00	5.00	1.77
$\underline{Y}_{(ch)}$	kg/ha	1010.00	3400.00	1910.60

Table 13. Soil profile classification for each site

Site #	County	Farmer's name	Soil profile
2010	Cnel. Dorrego	Biondo	Petrocalcic Argiudoll[a]
2020	Cnel. Dorrego	Vazquez	Petrocalcic Argiudoll
2030	Cnel. Dorrego	Lindstrong	Udic Haplustoll[a]
2040	Tres Arroyos	Verkuill	Typic Hapludoll[a]
2050	Tres Arroyos	Christiansen, A.	Natric Argialboll
2060	Tres Arroyos	Christiansen, B.	Aquic Argiudoll[a]
2070	Tres Arroyos	Candia	Petrocalcic Argiudoll
2080	San Cayetano	Vassolo, M.	Petrocalcic Argiudoll
2100	San Cayetano	Hoosgard, E.	Petrocalcic Argiudoll
2120	San Cayetano	Eguren	Typic Hapludoll[a]
2130	San Cayetano	Casili	Typic Hapludoll[a]
2140	Necochea	Betz	Petrocalcic Argiudoll
2150	Necochea	Esbensen	Typic Argiudoll
3011-12	Cnel. Dorrego	Clausen	Udic Argiustoll
3020	Cnel. Dorrego	Rodriguez	Petrocalcic Natralbol
3041-42	Cnel. Dorrego	Miramont	Petrocalcic Argiudoll
3050	Tres Arroyos	Jensen	Petrocalcic Hapludoll[a]
3061-62	Tres Arroyos	Dibbern	Typic Argialboll
3070	Tres Arroyos	Sydall	Typic Argialboll
3080	Tres Arroyos	Aizpurua	Typic Hapludoll[a]
3090	Tres Arroyos	Disalvo	Typic Hapludoll[a]

[a]Soils with less than 25% clay in the B horizon.

Table 13 (Continued)

Site #	County	Farmer's name	Soil profile
3101-02	Tres Arroyos	Valenzuela	Petrocalcic Argiudoll
3110	Tres Arroyos	Zubiri	Typic Argiudoll
3120	Tres Arroyos	Anderberg	Typic Argiudoll
3131	Tres Arroyos	Mayol	Petrocalcic Argiudoll
3140	Tres Arroyos	Vassolo, C.	Typic Argiudoll[a]
3180	San Cayetano	Hoosgard	Petrocalcic Argiudoll
3190	San Cayetano	Dahul	Typic Argiudoll
3201-02	San Cayetano	Baraco	Petrocalcic Argiudoll
3210	San Cayetano	Fernandez	Typic Argialboll
3221-22	San Cayetano	Vassolo, M.	Typic Argiudoll
3230	San Cayetano	Ruppel	Aquic Hapludoll[a]
3240	San Cayetano	Loidy	Petrocalcic Argiudoll
3260	Necochea	Larsen	Typic Argialboll
3270	Necochea	Balsategui	Typic Hapludoll[a]
3280	Necochea	Kier	Petrocalcic Argiudoll
3290	Necochea	Buss. S	Petrocalcic Hapludoll[a]
3301-02	Necochea	Irungaray	Petrocalcic Argiudoll
3320	Necochea	Hansen	Petrocalcic Argiudoll
3330	Necochea	Urrestarazu	Typic Argiudoll
3360	Loberia	Baron	Petrocalcic Argiudoll
3370	Loberia	Jauregy	Typic Argiudoll
3380	Balcarce	Alvear	Petrocalcic Argiudoll

Table 13 (Continued)

Site #	County	Farmer's name	Soil profile
3390	Gral. Pueyrredon	Bengolea	Typic Argiudoll
3400	Balcarce	Cechi	Typic Argiudoll
3410	Gral. Alvarado	Clemente	Aquic Argiudoll
3420	Gral. Alvarado	R. Guiñazu	Aquic Argiudoll
3430	Balcarce	Perez	Typic Natralboll
4021	Necochea	Mas	Aquic Argiudoll
4031	Tres Arroyos	Keergard	Aquic Argiudoll[a]
4041	San Cayetano	Keergard	Typic Argialboll
4051	Cnel. Pringles	Arosteguy	Typic Natralboll
4071	Cnel. Pringles	Buron	Typic Natralboll
4081	Tres Arroyos	Bruel	Petrocalcic Argiudoll
4091	Tres Arroyos	Cepeda	Typic Argiudoll
4101	Tres Arroyos	Alamberry	Aquic Hapludoll[a]
4111	San Cayetano	Cervetty	Petrocalcic Argiudoll
4131	San Cayetano	Bosch	Typic Argialboll
4141	Necochea	Larraburu	Typic Argiudoll
4161	Necochea	Llorente	Pachic Argiudoll
4171	Loberia	Durquet	Natric Argialboll
4191	Balcarce	Garcia	Typic Argiudoll
4211	Balcarce	Crovetto	Typic Argiudoll

Table 14. Regression analysis for Equation 6

R-Square	C.V.	Y Mean	Std. Dev.
0.541	18.11	1835.59	332.43

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	9	6142049.709	682449.967	6.17546	0.0001
Error	47	5193966.010	110509.915		
Corrected Total	56	11336015.719			

Source	df	Sequential SS	F-Value	Prob > F	Partial SS
d	1	3693340.419	33.42090	0.0001	759953.701
ni	1	31821.156	0.28795	0.6005	383686.023
w	1	390740.526	3.53580	0.0630	463101.820
Rni	1	23967.970	0.21689	0.6484	530730.437
dp	1	459549.324	4.15844	0.0444	268156.743
ca	1	527095.236	4.76966	0.0320	1146249.643
ni_1	1	199119.930	1.80183	0.1829	357877.265
omf	1	624215.366	5.64850	0.0204	673830.663
R_2	1	192199.777	1.73921	0.1907	192199.777

Source	B Values	T for HO:B=0	Prob > |T|	Std. Err. B
Intercept	1003.437	2.04113	0.0443	491.609
d	-26.245	-2.62236	0.0113	10.008
ni	9.605	1.86332	0.0654	5.155
w	-89.937	-2.04709	0.0437	43.934
Rni	-0.222	-2.19147	0.0314	0.101
dp	-1.097	-1.55774	0.1222	0.704
ca	56.999	3.22062	0.0027	17.698
ni_1	14.558	1.79956	0.0748	8.090
omf	-6.931	-2.46931	0.0164	2.806
R_2	1.604	1.31879	0.1907	1.216

Table 15. Regression analysis for Equation 7

R Square = 0.5857

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	12	986.43	82.203	6.48	0.0001
Error	55	697.67	12.685		
Total	67	1684.11			

	B-Value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	4.597				
pH	2.653	2.139	19.517	1.54	0.2201
om	2.087	0.709	109.773	8.65	0.0048
np	0.007	0.007	12.367	0.97	0.3278
ca	-0.264	0.156	36.590	2.88	0.0951
d	-0.330	0.065	324.735	25.60	0.0001
w	-0.897	0.354	81.508	6.43	0.0141
cb	-0.232	0.113	53.430	4.21	0.0449
so	-0.088	0.040	59.610	4.70	0.0345
tb	-0.202	0.067	114.286	9.01	0.0040
ni_1	-0.152	0.095	32.092	2.53	0.1174
re	0.626	0.215	107.229	8.45	0.0052
ta	0.294	0.113	84.708	6.68	0.0124

Table 16. Regression analysis for Equation 8

R Square = 0.551

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	7	1064.593	152.084	8.61	0.001
Error	49	865.715	17.667		
Total	56	1930.308			

	B-Value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	33.794				
pH	-4.731	2.532	61.689	3.49	0.0677
p	-0.539	0.173	170.204	9.63	0.0032
cb	0.271	0.121	88.154	4.99	0.0301
st	-2.270	1.521	39.358	2.23	0.1420
tb	0.235	0.088	123.768	7.01	0.0109
ta	-0.506	0.135	247.291	14.00	0.0005
ni	0.013	0.006	91.746	5.19	0.0271

Table 17. Regression analysis for Equation 9

R Square = 0.576

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	12	206279774.872	17189981.239	122.70	0.0001
Error	1081	151444030.929	140096.235		
Total	1093	357723805.802			

	B-Value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	2561.265				
N	4.777	1.377	1685777.749	12.03	0.0005
P	7.685	1.281	5038242.944	35.96	0.0001
NP	0.013	0.009	267282.626	1.91	0.1675
N^2	-0.016	0.012	263006.234	1.88	0.1709
P^2	-0.033	0.011	1074860.547	7.67	0.0057
Pp	-0.279	0.050	4275345.361	30.52	0.0001
Nd	-0.177	0.041	2608875.538	18.62	0.0001
cb	-9.386	2.010	3053701.237	21.80	0.0001
w	-149.049	9.095	37624913.220	268.56	0.0001
ca	8.506	4.260	558477.350	3.99	0.0461
sd	-0.388	0.023	37882479.985	270.40	0.0001
cc	6.512	3.376	521247.716	3.72	0.0540

Table 18. Regression analysis for Equation 10

R Square = 0.663 C.V. = 15.294% Y Mean = 2326.324 St. Dev. = 355.816

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	15	52925109.008	3528340.600	27.86881	0.0001
Error	212	26840335.777	126605.357		
Corrected total	227	79765444.785			

Source	df	Sequential SS	F-value	Prob > F	Partial SS
N	1	3808425.319	30.08108	0.0001	2017106.230
P	1	1998628.852	15.78629	0.0003	595351.089
N^2	1	72748.403	0.57641	0.5442	5466.824
P^2	1	7134.639	0.05635	0.8077	58780.665
ni_1	1	6117090.253	48.31620	0.0001	501000.357
Nni_1	1	9074.730	0.07168	0.7855	2325.320
Nd	1	13571341.464	107.19405	0.0001	241663.096
wd	1	15588597.620	123.12747	0.0001	14808592.745
dp	1	250603.050	1.97940	0.1572	489136.982
ta	1	9001088.903	71.09564	0.0001	9255590.226
p	1	4193.789	0.03312	0.8500	169251.429
Pp	1	94125.638	0.74346	0.6062	72543.046
Ncb	1	1542837.358	12.18619	0.0009	1715290.301
Pni	1	147503.607	1.16507	0.2813	137549.782
Rni	1	711715.369	5.62153	0.0176	711715.369

Table 18 (Continued)

Source	B-Values	T for H0:B=0	Prob > |T|	Std. Err. B
Intercept	694.648	2.75942	0.0064	251.737
N	24.517	3.99152	0.0003	6.142
P	6.218	2.16851	0.0293	2.867
N^2	-0.005	-0.20780	0.8300	0.024
P^2	-0.016	-0.68138	0.5036	0.023
Ni_1	13.824	1.98927	0.0451	6.949
Nni_1	-0.013	-0.13552	0.8875	0.096
Nd	-0.135	-1.38159	0.1649	0.098
wd	-29.467	-10.81511	0.0001	2.724
dp	-1.945	-1.96557	0.0477	0.989
ta	49.031	8.55019	0.0001	5.734
p	12.507	1.15622	0.2474	10.817
Pp	-0.110	-0.75696	0.5436	0.146
Ncb	-0.883	-3.68080	0.0006	0.239
Pni	-0.098	-1.04233	0.2988	0.094
Rni	-0.106	-2.37098	0.0176	0.044

Table 19. Regression analysis for Equation 11

R-Square = 0.59 C.V. = 17.02 Y-Mean = 2103.05 Std. Dev. = 358.13

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	15	159939456.087	10662630.405	83.13467	0.0001
Error	850	109018732.361	128257.332		
Corrected Total	865	268958188.449			

Source	df	Sequential SS	F-Value	Prob > F	Partial SS
N	1	5257728.297	40.993	0.0001	106949.661
P	1	11289868.384	88.025	0.0001	4812791.995
NP	1	395702.395	3.085	0.0755	282097.482
N^2	1	40766.367	0.317	0.5801	308742.984
P^2	1	748084.045	5.832	0.0152	1160081.419
Pp	1	35343126.629	275.564	0.0001	2529624.835
Nni_1	1	1197245.421	9.334	0.0027	778683.178
Nd	1	52743752.233	411.233	0.0001	350923.866
Pd	1	11839520.163	92.310	0.0001	435064.704
cb	1	732083.307	5.707	0.0162	3621064.896
w	1	14019866.102	109.310	0.0001	15613834.756
ca	1	5078054.336	39.592	0.0001	1422589.127
Nom	1	578409.268	4.509	0.0319	785678.545
tb	1	2096911.182	16.349	0.0002	346847.797
sd	1	18578335.950	144.852	0.0001	18578335.950

Table 19 (Continued)

Source	B-Values	T for H0:8=0	Prob > |T|	Std. Err. B
Intercept	2673.961	13.43746	0.0001	198.993
N	1.823	0.91316	0.6356	1.997
P	9.442	6.12572	0.0001	1.541
NP	0.015	1.48306	0.1344	0.010
N^2	-0.020	-1.55152	0.1170	0.013
P^2	-0.039	-3.00748	0.0031	0.013
Pp	-0.294	-4.44106	0.0001	0.066
Nni[1]	-0.093	-2.46399	0.0133	0.037
Nd	-0.077	-1.65411	0.0944	0.046
Pd	-0.078	-1.84177	0.0623	0.042
cb	-16.475	-5.31346	0.0001	3.100
w	-114.440	-11.03351	0.0001	10.372
ca	13.511	3.33042	0.0013	4.056
Nom	0.822	2.47504	0.0130	0.332
tb	3.547	1.64448	0.0963	2.157
sd	-0.384	-12.03545	0.0001	0.031

Table 20. Regression analysis for Equation 12

R-Square = 0.368

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	3	1441.355	480.451	10.29	0.0001
Error	53	2474.919	46.696		
Total	56	3916.275			

	B-Value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	23.444				
ca	-0.794	0.311	304.097	6.51	0.0136
ni_1	0.442	0.112	718.482	15.39	0.0003
R_1	-0.074	0.035	203.762	4.36	0.0415

Table 21. Regression analysis for Equation 13

R-Square = 0.648

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	5	1339.325	267.965	18.78	0.0001
Error	51	727.654	14.267		
Total	56	2067.480			

	B-value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	14.029				
nt_1	0.216	0.066	153.181	10.74	0.0019
ni_2	0.455	0.078	478.580	33.54	0.0001
ta	-0.221	0.099	70.764	4.96	0.0304
cb	-0.165	0.090	48.273	3.38	0.0717
f	-0.228	0.093	86.088	6.03	0.0175

Table 22. Regression analysis for Equation 14

R-Square = 0.484

Source	df	Sum of Squares	Mean Square	F-Value	Prob > F
Regression	3	8.200	2.733	16.59	0.0001
Error	53	8.732	0.164		
Total	56	16.932			

	B-Value	Std. Error	Type II SS	F-Value	Prob > F
Intercept	1.986				
ni	0.024	0.0053	3.458	20.99	0.0001
ni_3	0.029	0.0095	1.562	9.48	0.0033
R_1	-0.003	0.0020	0.537	3.26	0.0766